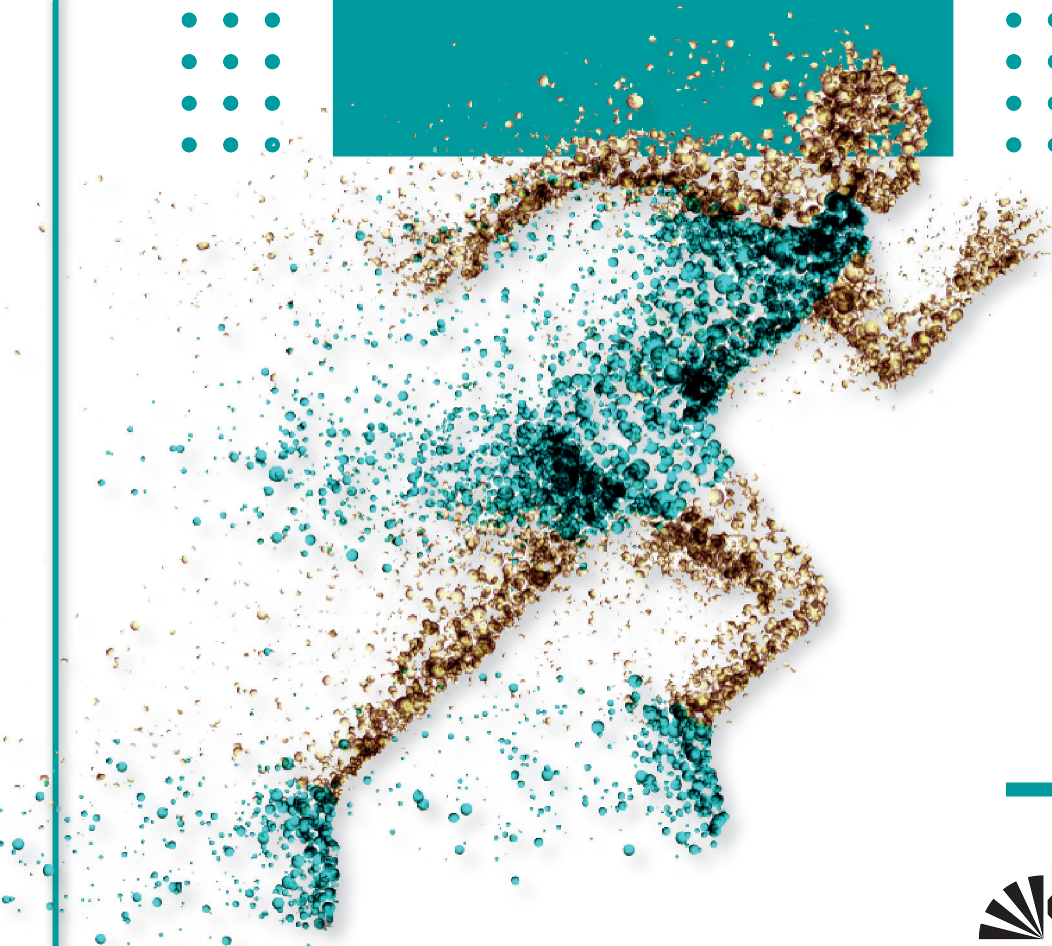
Influence of the Craniomandibular System on Human Postural Control with Special Consideration of Dynamic Stability

Cagla Kettner



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Summary

The control of posture is essential for daily living. It guarantees that movements are initiated and carried out as optimally as possible in both static and dynamic settings. Postural control entails controlling the body's position with respect to the environment for the dual purposes of balance and orientation. To detect and correct any imbalance, the sensory information from the somatosensory, visual and vestibular systems acting on the spinal and supraspinal structures of the central nervous system (CNS) are used. The CNS modifies the weighting and, consequently, the relative importance of sensory information based on the type of balance task being performed. Finally, the sensory input must be translated into motor commands to maintain the balance in a task-specific manner. Albeit the operation of these underlying postural control mechanisms is not completely known, impaired postural control has been linked to reduced participation in daily activities and an increased risk of falling.

A growing body of literature suggests that the craniomandibular system can impact postural control. Particularly, submaximal jaw clenching showed stabilizing effects on balance during upright standing. In contrast to static conditions, the effects of simultaneous jaw clenching during dynamic balance have not yet been investigated. Furthermore, a profound understanding of the potential mechanisms underlying the stabilizing effects of jaw clenching is still lacking. On this basis, the present thesis explores the effects of simultaneous submaximal jaw clenching on postural control in dynamic situations. Within this context, this thesis primarily focuses on the influences of jaw clenching on dynamic reactive and dynamic steady-state balance, with an additional emphasis on the underlying mechanisms at the kinematic and muscular levels. Furthermore, it also addresses if the effects of jaw clenching relate generally to dual-task benefits or specifically to jaw clenching.

The present thesis includes ten main chapters. In the first chapter (Chapter 1), a short motivation together with the outline of the thesis is given. In the following chapter (Chapter 2), the fundamentals of postural control as well as the craniomandibular system are introduced, and the interrelation of these systems is reviewed. Furthermore, the current state of the research regarding the influences of jaw clenching particularly on postural control is provided. Chapter 3 sums up the aims and the scope of this thesis.

The subsequent chapters (Chapters 4 to 8) encompass five research articles that aimed to investigate the effects of simultaneous submaximal jaw clenching on dynamic reactive

balance (Chapter 4-6) and dynamic steady-state balance (Chapter 7-8). Each of these research articles has been published in an international peer-reviewed journal.

The study given in Chapter 4 considers the modulation of postural control during a dynamic reactive balance task with different simultaneous oral-motor activities, and aims to answer the question how jaw clenching, tongue pressing and habitual stomatognatic behavior influence dynamic reactive balance performance. In this study, dynamic reactive balance was assessed by using an oscillating platform. A custom-made release system was used to apply mechanical perturbations in one of the four possible directions. In addition to the dynamic reactive balance performance, the segmental kinematics were investigated for a deeper understanding of the results. The findings revealed that jaw clenching can improve dynamic reactive balance but the favorable benefits appear to be task-specific rather than general. Tongue pressing appears not to have any effects on dynamic reactive balancing performance. In comparison to tongue pressing and habitual stomatognatic behavior conditions, the mean speeds of the analyzed segments were overall lower for the jaw clenching condition.

Chapter 5 presents the follow-up study of the previous one, and focuses on the reflex activities and co-contraction patterns to establish a more comprehensive view of the occurring changes due to simultaneous oral-motor activities. More specifically, this study investigated the muscle activity (i.e. iEMG) and the co-contraction behavior of the leg and trunk muscles during the critical reflex phases under the influence of jaw clenching, tongue clenching and habitual stomatognathic behavior. Only the direction of perturbation in which an improvement in dynamic balance performance was observed with simultaneous jaw clenching was analyzed. The findings could not explain why jaw clenching leads to better dynamic reactive balance compared with tongue pressing or habitual stomatognatic behavior conditions. Neither the muscle activity nor the co-contraction pattern analysis revealed a general neuromechanical effect of jaw clenching on dynamic reactive balancing performance.

The study in Chapter 6 investigates the neuromechanical effects occurring after the automation of jaw clenching task. Based on the research findings on the dual-task paradigm during balance, it can be argued that jaw clenching is a secondary task when it is simultaneously performed during balance tasks, therefore, the effects of jaw clenching are not due to specific neuromechanical effects of the jaw clenching activity but related to the dual-task situation in general. It has not yet been investigated whether the effects are mainly related to the dual-task benefits or the jaw clenching itself. This study addressed this issue with an intervention study and investigated the effects of jaw clenching on dynamic reactive balance task performance after 1 week of jaw clenching training to

examine whether the effects were a result of a dual-task situation. The results revealed that the automation of the jaw clenching task had no discernible effects on dynamic reactive balance performance. Jaw clenching appeared to be associated with some modifications in reflex activities but the effects were restricted to anterior-posterior perturbations. High learning effects of the dynamic reactive balance task were detected, which may have masked the jaw clenching effects. More studies with different balance tasks with lower learning effects and longer intervention periods were suggested to be necessary.

After the previous chapters have focused on dynamic reactive balance, Chapter 7 provides the first study investigating the effects of simultaneous submaximal jaw clenching during dynamic steady-state balance. Particularly, the steady-state phase of the dynamic balance task after the compensation of the perturbation on the oscillating platform was analyzed. In various postural control studies, the center of mass (CoM) is proposed as the controlled variable albeit missing experimental verification. Nevertheless, the CoM was shown to be an important parameter in terms of balance. This study investigated if jaw clenching has effects on sway, control and stability of CoM during dynamic steady-state balance. An uncontrolled manifold approach with a whole-body joint kinematics model was utilized besides the analysis of spatial and temporal variability characteristics of the CoM sway. The results of this comprehensive analysis provided no effects of jaw clenching or tongue pressing on the sway, control or stability of the CoM.

Similar to the previous one, the study given in Chapter 8 focused on jaw clenching effects on dynamic steady-state balance. In this study, another dynamic balance task was used. More precisely, a stabilometer was used to assess the dynamic steady-state balance. A three-armed intervention study design aimed to answer three research questions: first, if simultaneous submaximal jaw clenching can improve dynamic steady-state balance; second, if the effects persist after the jaw clenching task loses its novelty and potential dual-task benefits associated with it; and third, if the improved dynamic steady-state balance performance is related with decreased activity of posture-related muscles. The results revealed that simultaneous submaximal jaw clenching improves dynamic steady-state balance performance on the stabilometer. These effects persist even when the novelty of the secondary task (i.e. jaw clenching) decreases. The secondary finding demonstrated that the learning effects of the used dynamic steady-state balance task were high, and might have masked the effects of balance training. Improved dynamic steady-state balance performance led to decreased activities of posture-related muscles, indicating better movement efficiency. However, there were no jaw clenching-related alterations in muscle activities.

Chapter 9 provides a general discussion of the findings from the presented research. The combination of the findings from these five studies provides a more comprehensive understanding of how simultaneous submaximal jaw clenching affects balance in dynamic situations. In essence, this thesis provides additional evidence for the impact of the craniomandibular system on the postural control system, yet it does not fully identify the underlying neuromechanical mechanisms of the effects. The partially conflicting results may be attributed to the task-specificity of balance tasks but it can also be due to the yet undiscovered effects of jaw clenching masked by the high learning effects of the widespread balance tasks used in this thesis. Further research is recommended to fully assess the potential of jaw clenching and to better understand the underlying neuromechanical effects. The thesis closes with a general conclusion in Chapter 10.

Zusammenfassung

Die Kontrolle der Körperhaltung ist für das tägliche Leben unerlässlich. Sie gewährleistet, dass Bewegungen sowohl in statischen als auch in dynamischen Situationen möglichst optimal eingeleitet und ausgeführt werden. Bei der Haltungskontrolle geht es darum, die Orientierung und Balance des Körpers zu koordinieren, indem seine Position im Verhältnis zur Umgebung angepasst wird. Um eine Dysbalance zu erkennen und zu korrigieren, werden die sensorischen Informationen des somatosensorischen, visuellen und vestibulären Systems genutzt, die auf die spinalen und supraspinalen Strukturen des Zentralnervensystems (ZNS) wirken. Das ZNS ändert die Gewichtung und damit die relative Bedeutung der sensorischen Informationen in Abhängigkeit von der Art der zu bewältigenden Gleichgewichtsaufgabe. Schließlich muss der sensorische Input in motorische Befehle umgesetzt werden, um das Gleichgewicht aufgabenspezifisch halten zu können. Obwohl die Funktionsweise dieser zugrundeliegenden Mechanismen der Haltungskontrolle nicht vollständig bekannt ist, wurde eine gestörte Haltungskontrolle mit einer verminderten Teilnahme an täglichen Aktivitäten und einem erhöhten Sturzrisiko in Verbindung gebracht.

Eine wachsende Zahl von Veröffentlichungen deutet darauf hin, dass das kraniomandibuläre System die Haltungskontrolle beeinflussen kann. Insbesondere submaximales Kieferpressen zeigte stabilisierende Auswirkungen auf das Gleichgewicht beim aufrechten Stehen. Im Gegensatz zu statischen Bedingungen sind die Auswirkungen des gleichzeitigen Zusammenpressens der Kiefer während dynamischer Gleichgewichtsaufgaben noch nicht untersucht worden. Darüber hinaus fehlt noch ein tiefes Verständnis der möglichen Mechanismen, die den stabilisierenden Effekten des Kieferpressens zugrunde liegen. Auf dieser Grundlage untersucht die vorliegende Arbeit die Auswirkungen des gleichzeitigen submaximalen Kieferpressens auf die menschliche Haltungskontrolle in dynamischen Situationen. In diesem Zusammenhang konzentriert sich diese Arbeit in erster Linie auf die Einflüsse des Kieferpressens auf das dynamische reaktive und das dynamische steady-state Gleichgewicht, mit einem zusätzlichen Schwerpunkt auf den zugrunde liegenden Mechanismen auf kinematischer und muskulärer Ebene. Darüber hinaus wird untersucht, ob sich die Auswirkungen des Kieferpressens allgemein auf die Dual-Task-Bedingungen oder speziell auf das Kieferpressen beziehen.

Die vorliegende Arbeit umfasst zehn Hauptkapitel. Im ersten Kapitel wird zunächst die dieser Dissertationsschrift zugrunde liegende Fragestellung motiviert und die Gliederung der Arbeit gegeben. Im darauffolgenden Kapitel 2 werden die Grundlagen der menschli-

chen Haltungskontrolle sowie des craniomandibulären Systems vorgestellt und die Zusammenhänge zwischen diesen Systemen erläutert. Darüber hinaus wird der aktuelle Stand der Forschung zu den Einflüssen des Kieferpressens insbesondere auf die menschliche Haltungskontrolle dargestellt. Kapitel 3 fasst die Ziele und den Aufbau der vorliegenden Arbeit zusammen.

Die folgenden Kapitel 4 bis 8 umfassen fünf wissenschaftliche Artikel, die die Auswirkungen des gleichzeitigen submaximalen Kieferpressens auf das dynamische reaktive Gleichgewicht (Kapitel 4-6) und das dynamische steady-state Gleichgewicht (Kapitel 7-8) untersuchen. Jeder dieser wissenschaftlichen Artikel wurde in einer internationalen Fachzeitschrift mit Peer-Review Verfahren veröffentlicht.

Die in Kapitel 4 vorgestellte Studie untersucht die Modulation der posturalen Kontrolle während einer dynamischen reaktiven Gleichgewichtsaufgabe mit verschiedenen gleichzeitigen oral-motorischen Aktivitäten und zielt darauf ab, die Frage zu beantworten, wie Kieferpressen, Zungenpressen und habituelles stomatognatisches Verhalten die dynamische reaktive Gleichgewichtsleistung beeinflussen. In dieser Studie wurde das dynamische reaktive Gleichgewicht mit Hilfe einer oszillierenden Plattform untersucht. Ein speziell angefertigtes Auslösesystem wurde verwendet, um mechanische Störungen in einer der vier möglichen Richtungen zu erzeugen. Neben der dynamischen reaktiven Gleichgewichtsleistung wurde auch die segmentale Kinematik untersucht, um die auf Leistungsebene identifizierten Effekte besser erklären zu können. Die Ergebnisse zeigten, dass das Zusammenpressen der Kiefer das dynamische reaktive Gleichgewicht verbessern kann, aber die positiven Auswirkungen scheinen eher aufgabenspezifisch als allgemeingültig zu sein. Zungenpressen scheint keine Auswirkungen auf die dynamische reaktive Gleichgewichtsleistung zu haben. Im Vergleich zu den Bedingungen des Zungenpressens und des habituellen Kieferpressens waren die mittleren Geschwindigkeiten der untersuchten Segmente unter der Bedingung des Zusammenpressens der Kiefer insgesamt niedriger.

Kapitel 5 stellt die Folgestudie der vorangegangenen Studie dar und konzentriert sich auf die Reflexaktivitäten und Ko-Kontraktionsmuster, um einen umfassenderen Überblick über die Veränderungen zu erhalten, die durch das gleichzeitige submaximale Kieferpressen auftreten. Konkret wurden in dieser Studie die Muskelaktivität (d.h. iEMG) und das Ko-Kontraktionsverhalten der Bein- und Rumpfmuskulatur während der kritischen Reflexphasen unter dem Einfluss von Kieferpressen, Zungenpressen und habituellem stomatognatischem Verhalten untersucht. Es wurde nur die Richtung der Störung analysiert, in der eine Verbesserung der dynamischen Gleichgewichtsleistung bei gleichzeitigem Zusammenpressen der Kiefer beobachtet wurde. Die Ergebnisse konnten nicht erklären, warum Kieferpressen zu einem besseren dynamischen reaktiven Gleichgewicht führt als Zungenpressen oder habituelles Kieferpressen. Weder die Muskelaktivität noch die Analyse der Ko-Kontraktionsmuster zeigten einen allgemeinen neuromechanischen Effekt des Kieferpressens auf die dynamische reaktive Gleichgewichtsleistung.

Die Studie in Kapitel 6 untersucht die neuromechanischen Effekte, die nach der Automatisierung der Aufgabe des Kieferpressens auftreten. Basierend auf den Forschungsergebnissen zum Dual-Task-Paradigma im Kontext des Lösens von Gleichgewichtsaufgaben kann argumentiert werden, dass das Kieferpressen eine sekundäre Aufgabe ist, wenn es gleichzeitig mit Gleichgewichtsaufgaben durchgeführt wird, daher könnten die Effekte des Kieferpressens nicht auf spezifische neuromechanische Effekte der Kieferpressaktivität zurückzuführen sein, sondern hängen mit der Dual-Task-Situation im Allgemeinen zusammen. Es ist noch nicht untersucht worden, ob die Effekte hauptsächlich mit den Vorteilen der Dual-Task-Situation oder mit dem Kieferpressen selbst zusammenhängen. In dieser Studie wurde dieses Problem mit einer Interventionsstudie angegangen und die Auswirkungen des Kieferpressens auf die Leistung bei dynamischen reaktiven Gleichgewichtsaufgaben nach einem einwöchigen Kieferpressentraining untersucht, um zu prüfen, ob die Auswirkungen auf eine Dual-Task-Situation zurückzuführen sind. Die Ergebnisse zeigten, dass die Automatisierung der Aufgabe des Kieferpressens keine erkennbaren Auswirkungen auf die dynamische reaktive Gleichgewichtsleistung hatte. Das Zusammenpressen des Kiefers schien mit einigen Modifikationen der Reflexaktivitäten verbunden zu sein, aber die Auswirkungen waren auf anterior-posteriore Störungen beschränkt. Es wurden hohe Lerneffekte bei der dynamisch-reaktiven Gleichgewichtsaufgabe festgestellt, die möglicherweise die Auswirkungen des Kieferpressens überdeckten. Weitere Studien mit anderen Gleichgewichtsaufgaben mit geringeren Lerneffekten und längeren Interventionszeiträumen wurden als notwendig erachtet.

Nachdem sich die vorangegangenen Kapitel auf das dynamische reaktive Gleichgewicht konzentriert haben, bietet Kapitel 7 die erste Studie, in der die Auswirkungen des gleichzeitigen submaximalen Kieferpressens während des dynamischen steady-state Gleichgewichts untersucht wurden. Insbesondere wurde die steady-state Phase der dynamischen Gleichgewichtsaufgabe nach der Kompensation der Perturbation auf der oszillierenden Plattform analysiert. In verschiedenen Studien zur Haltungskontrolle wird der Körperschwerpunkt (KSP) als Kontrollvariable vorgeschlagen, obwohl eine experimentelle Überprüfung fehlt. Dennoch wurde gezeigt, dass der KSP ein wichtiger Parameter für das Gleichgewicht ist. In dieser Studie wurde untersucht, ob das Zusammenpressen der Kiefer Auswirkungen auf das Schwanken, die Kontrolle und die Stabilität des CoM während des dynamischen Gleichgewichts hat. Neben der Analyse der räumlichen und zeitlichen Variabilität des KSPs wurde ein Uncontrolled Manifold Ansatz mit einem Ganzkörper-Gelenkkinematikmodell verwendet. Die Ergebnisse dieser umfassenden Analyse zeigten keine Auswirkungen des Zusammenpressens der Kiefer oder des Zungenpressens auf die Schwankung, die Kontrolle oder die Stabilität des KSPs.

Ähnlich der vorhergehenden Studie konzentrierte sich die Studie in Kapitel 8 auf die Auswirkungen des Zusammenpressens der Kiefer auf das dynamische steady-state Gleichgewicht. In dieser Studie wurde eine andere dynamische Gleichgwichtsaufgabe verwendet. Genauer gesagt wurde ein Stabilometer verwendet, um das dynamische steady-state Gleichgewicht zu bewerten. Mit Hilfe eines dreiarmigen Interventionsstudien-Designs sollten drei Forschungsfragen beantwortet werden: erstens, ob gleichzeitiges submaximales Kieferpressen das dynamische Gleichgewicht verbessern kann; zweitens, ob die Effekte anhalten, nachdem die Aufgabe des Kieferpressens ihre Neuartigkeit und die die damit verbundenen potenziellen Dual-Task Vorteile verloren hat; und drittens, ob die verbesserte Leistung des dynamischen Gleichgewichts mit einer verringerten Aktivität der haltungsbezogenen Muskeln zusammenhängt. Die Ergebnisse zeigten, dass gleichzeitiges submaximales Kieferpressen die dynamische Gleichgewichtsleistung auf dem Stabilometer verbessert. Diese Effekte bleiben auch dann bestehen, wenn die Neuartigkeit der sekundären Aufgabe (d. h. das Zusammenpressen der Kiefer) abnimmt. Das sekundäre Ergebnis zeigte, dass die Lerneffekte der verwendeten dynamischen Gleichgewichtsaufgabe hoch waren und die Effekte des Gleichgewichtstrainings überdeckt haben könnten. Eine verbesserte dynamische steady-state Gleichgewichtsleistung führte zu einer geringeren Aktivität der haltungsrelevanten Muskeln, was auf eine gesteigerte Bewegungseffizienz hindeutet. Es gab jedoch keine mit dem Kieferpressen zusammenhängenden Veränderungen der Muskelaktivitäten.

Kapitel 9 enthält eine allgemeine Diskussion der Ergebnisse aus den vorgestellten Forschungsarbeiten. Die Kombination der Ergebnisse dieser fünf Studien ermöglicht ein umfassenderes Verständnis darüber, wie gleichzeitiges submaximales Kieferpressen das Gleichgewicht in dynamischen Situationen beeinflusst. Im Wesentlichen liefert diese Arbeit zusätzliche Beweise für den Einfluss des kraniomandibulären Systems auf das Haltungskontrollsystem, aber sie identifiziert nicht vollständig die zugrunde liegenden neuromechanischen Mechanismen, die diesen Einfluss ausmachen. Die teilweise widersprüchlichen Ergebnisse lassen sich durch die Aufgabenspezifität der Gleichgewichtsaufgaben erklären, können aber auch auf die noch unentdeckten Auswirkungen des Kieferpressens zurückzuführen sein, die durch die hohen Lerneffekte der verwendeten dynamischen Gleichgewichtsaufgaben überdeckt werden. Weitere Untersuchungen werden empfohlen, um das Potenzial des Kieferpressens vollständig zu erfassen und die zugrunde liegenden neuromechanischen Effekte besser zu verstehen. Die vorgelegte Dissertationsschrift schließt in Kapitel 10 mit einer Konklusion.

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1 General Introduction

1.1 Motivation

Postural control can be defined as the control of the body's position in relation to its surroundings for the dual purposes of balance and orientation (Macpherson & Horak, 2013) and it is vital in everyday living of human. Good postural control is linked to a lower risk of falls (Rubenstein, 2006) and injuries (Hrysomallis, 2007), whereas poor postural control can lead to a loss of functional independence and restricted involvement in everyday activities.

The postural control system is the consequence of a complex interplay between the nervous and musculoskeletal systems. As a result, inputs from somatosensory (e.g., joint receptors), visual and vestibular systems are used to determine the position and movement of the body in relation to its surroundings and translated into motor commands to maintain the balance in a task-specific manner (Shumway-Cook & Woollacott, 2017). The unconscious and (semi-) automated control of posture is sensitive to several internal and environmental factors. For example, the lack of sensory information, neuromechanical deficiencies or external perturbations can considerably disrupt postural control processes (Horak, 2006). The degenerative decline of the sensory and neuromechanical systems, as particularly seen in the elderly, may substantially worsen posture and its control (Granacher, Muehlbaue, et al., 2011). Ultimately, the number of falls may increase due to impaired balance and orientation. Consequently, falls and their medical impacts pose a serious risk to the quality of life of individuals, and may lead to the loss of independence or even death (Blake et al., 1988). On this basis, the conduction of research on postural control and its influencing factors is particularly important.

Postural control was shown to be influenced by many factors such as age (e.g., Henry & Baudry, 2019), neurological diseases (e.g., Delafontaine et al., 2020), training (e.g., Sherrington et al., 2020) and mood states (e.g., Cuccia & Caradonna, 2009). Recently, a growing body of literature indicated that the craniomandibular system can also affect the postural control system (Julià-Sánchez et al., 2015). Particularly, jaw clenching during balance tasks was shown to contribute to the stabilization of the body, therefore improving balance. The shown effects were, however, limited to static conditions particularly to upright standing (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015), and have not yet been investigated under dynamic conditions. In addition, the underlying neuromechanical mechanisms remain still unknown. Furthermore, prior studies have demonstrated that the sensory information associated with dental occlusion is used more strongly when more challenging postural control conditions are present (e.g., unstable or complex balance tasks, or external perturbations (Julià-Sánchez et al., 2016, 2019; Tardieu et al., 2009)). On this basis, it can be argued that the effects of simultaneous jaw clenching would most likely be more pronounced in challenging or dynamic balance tasks as opposed to static ones.

Focusing on the above-mentioned research gap, this thesis aimed to investigate the effects of simultaneous jaw clenching on dynamic balance, more precisely on dynamic reactive and dynamic steady-state balance. A thorough understanding of the notable features and underlying mechanisms of jaw clenching on dynamic balance discovered within this thesis could broaden the limits of the current state of knowledge on the postural control and craniomandibular systems. The gained insights may ultimately be used for fall prevention, clinical assessments as well as training tools.

1.2 Outline of the thesis

The present thesis includes ten main chapters. In this current chapter (Chapter 1) a general introduction is provided. Chapter 2 covers the fundamentals of postural control as well as of the craniomandibular system. Furthermore, the interrelation of the postural control with the craniomandibular system is reviewed. Finally, the current state of the knowledge regarding the effects of jaw clenching particularly on postural control is provided. Chapter 3 sums up the aims and scope of the present thesis.

The subsequent chapters (Chapters 4 to 8) encompass five research articles that aimed to answer previously deduced research questions (Chapter 3). Each research article has been published in an international peer-reviewed journal:

- Chapter 4: Study I - Modulation of Postural Control - Dynamic Reactive Balance

Fadillioglu, C., Kanus, L., Möhler, F., Ringhof, S., Schindler, H. J., Stein, T.*, & Hellmann, D.* (2022). Influence of controlled masticatory muscle activity on dynamic reactive balance. *Journal of Oral Rehabilitation, 49*, 327–336. [*These authors have contributed equally to this work.]

- Chapter 5: Study II - Modulation of Reflex Activities – Dynamic Reactive Balance

Hellmann, D*., Fadillioglu, C.*, Kanus, L., Möhler, F., Schindler, H. J., Schmitter, M., Stein, T. & Ringhof, S. (2023). Influence of oral-motor tasks on postural muscle activity during dynamic reactive balance. *Journal of Oral Rehabilitation*, *00*, 1-9. [*These authors have contributed equally to this work.]

- Chapter 6: Study III - Modulation of Jaw Clenching Effects after Jaw Clenching Training

Fadillioglu, C., Kanus, L., Möhler, F., Ringhof, S., Hellmann, D.*, & Stein, T.* (2023). Effects of jaw clenching on dynamic reactive balance task performance after 1-week of jaw clenching training. *Frontiers in Neurology*, *14*, 1-13. [*These authors have contributed equally to this work.]

- Chapter 5: Study IV - Modulation of Center of Mass Movement

Fadillioglu, C., Kanus, L., Möhler, F., Ringhof, S., Hellmann, D.*, & Stein, T.* (2022). Influence of Controlled Stomatognathic Motor Activity on Sway, Control and Stability of the Center of Mass During Dynamic Steady-State Balance—An Uncontrolled Manifold Analysis. *Frontiers in Human Neuroscience*, *16*, 1-13. [*These authors have contributed equally to this work.]

- Chapter 8: Study V - Modulation of Postural Control - Dynamic Steady-State Balance

Fadillioglu, C., Kanus, L., Möhler, F., Ringhof, S., Hellmann, D.*, & Stein, T.* (2023). Persisting effects of jaw clenching on dynamic steady-state balance. *PLOS ONE, 19(2)* 1-12. [*These authors have contributed equally to this work.]

Chapter 9 summarizes the main findings of the presented research articles and provides a general discussion as well as implications and recommendations for future research. The thesis ends with a conclusion given in Chapter 10.

2 Theoretical Background

2.1 Postural control

Postural control is essential for daily life of human. Good postural control is associated with a decreased risk of falls (Rubenstein, 2006) and injuries (Hrysomallis, 2007), whereas impaired postural control may lead to the loss of functional independence as well as to reduced participation in daily life. By definition, postural control involves the control of the body's position in space to establish orientation and stability (Shumway-Cook & Woollacott, 2017). Postural orientation involves the active alignment of the body segments with respect to each other, as well as with the environment (Horak, 2006). Whereas, postural balance refers to the ability to control the center of mass (CoM) with respect to the base of support (BoS). The term balance is used to describe the dynamics of body posture to prevent falling (Winter, 1995), and it is often used interchangeably with the terms (postural) stability or (postural) equilibrium (Horak, 2006; Shumway-Cook & Woollacott, 2017). In this thesis, the term balance is used in the sense of (postural) stability or (postural) equilibrium.

2.1.1 Types of balance

In the older literature (e.g., Fleishman, 1964; Schnabel et al., 2016) postural balance was often considered as a general ability. Consequently, balance has usually been assessed by using general tests such as one-leg stance regardless of the relevant factors, e.g., type of sports involved or training conditions. For many years, this approach has been critically discussed, and task-specificity of postural balance has been emphasized (e.g., Giboin et al., 2015; Kümmel et al., 2016; Ringhof & Stein, 2018).

Even though there is not yet a universal single definition, in the literature it is commonly distinguished between static and dynamic balance. In various sources, dynamic balance is further divided into three sub-categories: steady-state, proactive (anticipatory) and reactive (compensatory) balance (Kiss, Schedler, & Muehlbauer, 2018; Lesinski et al., 2015a; Shumway-Cook & Woollacott, 2017).

Besides the task-specific characteristics of balance, the correlations between static and dynamic balance were shown to be extremely low (Granacher, Bridenbaugh, et al., 2011; Kiss, Schedler, & Muehlbauer, 2018), and different mechanisms are suggested to control balance under static and dynamic conditions (Shimada et al., 2003). On this basis, it is important to consider different balance types individually.

2.1.1.1 Static steady-state balance

Static steady-state balance comprises unperturbed conditions, in which BoS does not change, for example during quiet standing or sitting. It is often also called “static balance”. However, this term is also misleading because in fact the body, therefore the CoM, is always in motion, even during upright standing (Macpherson & Horak, 2013). The main reason for that is that the human body is mechanically unstable because it consists of many segments that are linked by joints (Macpherson & Horak, 2013). From a mechanical perspective, the maintenance of static steady-state balance requires that the downward projection of the CoM stays within the BoS. Thereby, the area and location of the BoS do not change throughout the entire process (Shumway-Cook & Woollacott, 2017).

2.1.1.2 Dynamic steady-state balance

Dynamic steady-state balance involves fundamentally the maintenance of balance after self-initiated disturbances (e.g., swinging the lower leg to step forward) during dynamic conditions, for example during walking or running. When walking the vertical projection of the CoM stays continuously out of the BoS, therefore, the body is in a continuous state of imbalance. By placing the swinging leg forward, the BoS is actively moved under the falling CoM, ultimately a possible fall situation is prevented (Shumway-Cook & Woollacott, 2017).

2.1.1.3 Dynamic proactive balance

The main difference between reactive and proactive balance is the predictability of the perturbations. In the case of proactive balance, the perturbation is anticipated and compensated before the balance is lost (Shumway-Cook & Woollacott, 2017; Winter, 1995). An example from real life is the landing after a counter-movement jump or lifting an object from the ground (Shumway-Cook & Woollacott, 2017).

2.1.1.4 Dynamic reactive balance

Dynamic reactive balance can be defined as the compensation of an unpredicted postural disturbance to maintain the balance. These postural disturbances are mostly whole-body perturbations, caused by surface translations and rotations (Lesinski et al., 2015a; Shumway-Cook & Woollacott, 2017). Thereby, the aim is to bring the downward projection of CoM back into the BoS, either by changing the CoM, the BoS, or both of them. An example from real life is the slipping due to wet floors (Gielo-Perczak et al., 2006; S. Wang et al., 2022).

2.1.2 Assessment of balance

Balance assessment can be divided into three main categories: functional assessments, system assessments, and quantitative assessments (Horak, 1997; Mancini & Horak, 2010).

Functional assessments are helpful to monitor the balance status and changes with intervention. The usually used tests rate performance on a set of scale-based motor tasks, e.g., total time in a particular posture (Horak, 1997).

System assessments are helpful in identifying the disordered subcomponents or mechanisms underlying balance control, and therefore, help clinicians direct specific treatments for their patients. For example, the Balance Evaluation Systems Test (BESTest) belongs to this category (Horak et al., 2009). BESTest comprises 6 different balance control systems such as “Biomechanical Constraints” or “Stability in Gait” so that a specific rehabilitation programm can be designed depending on the type of balance deficits. In this way, BESTest allows clinicians to determine the type of balance problems to create targeted treatments for their patients.

Objective assessments are mostly based on the quantitative assessment methods of posturography, which quantifies the body sway mostly by using force recordings (Duarte et al., 2010; Richmond et al., 2021). Posturography is further divided into static and dynamic posturography.

Static posturography is in fact not static but aims to assess postural sway during upright standing. It has been traditionally assessed in a laboratory by using force plates to assess the center of pressure (CoP) (Duarte et al., 2010). Despite their accuracy and popularity, they are also disadvantageous due to their high costs and restricted use to laboratory conditions. Recent innovations resulted in alternative inexpensive and portable tools for the quantification of CoP, such as balance plates (Richmond et al., 2021).

Dynamic posturography involves mostly the application of perturbations which are usually mechanical and generated by using movable, computerized support surfaces (Freyler et al., 2015; Giboin et al., 2015; Mancini & Horak, 2010). Various devices have been developed for the balance assessment (Petró et al., 2017). For example, the oscillating platforms (e.g., Posturomed, Figure 2.1a) are used to apply mechanical perturbations, and ultimately to assess dynamic reactive balance. These systems consist of a rigid platform that is connected to a main frame by springs. The platform can swing freely in the plane horizontally to the ground. Typically, an electro-magnetic (Freyler et al., 2015; D. Schmidt et al., 2015) or motorized system (Petró et al., 2017; Ringhof & Stein, 2018) is used to apply perturbations.

Another device that is mostly used for dynamic posturography is the balance board. These can be categorized according to their rotation axis (Petró et al., 2017). Sagittal axis balance board (Petró et al., 2017), also known as a stabilometer, is a commonly used device to assess dynamic steady-state and proactive balance in various studies (Kiss, Brueckner, & Muehlbauer, 2018; Lehmann, 2022; Muehlbauer et al., 2022; Orrell et al., 2006). The task to be performed is mostly to keep the platform horizontal to the ground by balancing the weight distribution in a bipedal stance (Petró et al., 2017).

Another possibility is to use sensory perturbations to specifically manipulate one or more sensory systems used for postural control (Mancini & Horak, 2010). These types of perturbations ultimately help to understand the contribution and flexible reweighing of each sensory information that contributes to postural control in altered conditions for example by using virtual reality technologies (Ida et al., 2022; Ketterer et al., 2022).

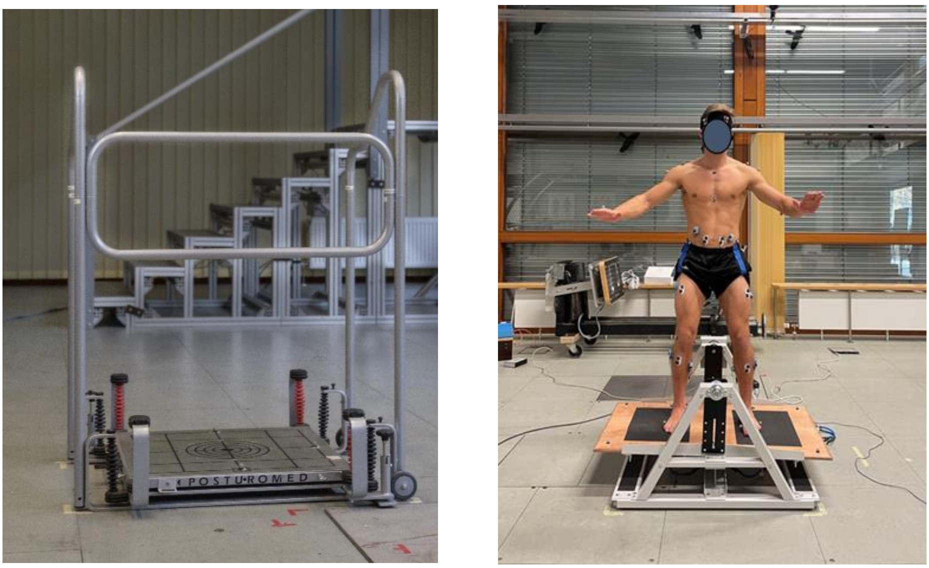

Figure 2.1: a. Posturomed, the oscillating platform. b. Stabilometer, the sagittal axis balance board.

2.1.3 Sensory aspects of postural control

The postural control system is a result of the complex interaction of the neural and musculoskeletal systems. Thereby, the inputs from somatosensory (proprioceptive, cutaneous, and joint receptors), visual and vestibular systems are used as the source of information about the position and the movement of the body with respect to the environment (Shumway-Cook & Woollacott, 2017). In the case of standing on a rigid and stable support surface with sufficient light in the environment, a healthy person mostly relies on somatosensory inputs at 70%, vestibular inputs follow them at 20%, and finally, visual inputs come at 10% (Horak, 2006). Depending on the environmental conditions, movement goals and availability of the sensory information, the CNS modifies the relative sensitivity or weighting of different sensory inputs (Peterka, 2002; Peterka & Loughlin, 2004; Macpherson & Horak, 2013). For example, when standing on an unstable surface, the sensory weighting shifts in favor of vestibular and visual inputs (Horak, 2006).

Somatosensory inputs are essential for the timing and direction of automatic postural responses. Thereby, somatosensory fibers provide the somatosensory information, and they have two main characteristics: they are large in diameter and respond fast. The largest and fastest sensory fibers are the Ia afferents from muscle spindles and Ib afferents from Golgi tendon organs. Fibers located in cutaneous mechanoreceptors also contribute to somatosensory input production. Somatosensory inputs are ultimately used to build the neural map for the position of body segments with respect to each other and the support surface (Macpherson & Horak, 2013).

Vestibular inputs are important for the assessment of body tilt with respect to gravity as well as the direction of the body sway. Thereby, the otolithic organs of the vestibular apparatus provide information about the direction of gravity and the semicircular canals about the velocity of head movement. Unlike somatosensory inputs, vestibular information is not important for the timing of the postural responses but for the directional tuning of them. Vestibular information becomes especially critical in case of reduced visual inputs (e.g., at night in a dark room) and unstable support surfaces (e.g., on a boat) (Macpherson & Horak, 2013).

Visual inputs provide information about the orientation and motion from both near and far. They help to reduce body sway by providing stabilizing cues and orienting the body in the environment. They also provide information for anticipatory postural adjustments during voluntary movements. For example, during planning where to place the feet during stair walking with obstacles on the steps. Visual inputs and their changes can have a powerful influence on postural orientation. On the other hand, processing the visual information is too slow, and therefore, does not affect the postural responses significantly during balance recovery after sudden disturbances (Macpherson & Horak, 2013).

2.1.4 Central aspects of postural control

In general, postural control has two basic modes. The first one is the “feedback mode” which comprises compensatory postural adjustments to maintain the balance. The second one is the “feedforward mode” which basically refers to the anticipatory postural adjustments to sustain the balance. In this mode, potential postural perturbations are foreseen and avoided by properly self-initiated counter-movements. However, neural control of balance is not binary, e.g., not either in the feedback or feedforward mode but rather a combination of these modes is in use (Taube & Gollhofer, 2010). To date, there is little consensus on how the postural control mechanisms are coordinated within the CNS (Murnaghan et al., 2014). It is suggested that posture control is distributed in all levels of the CNS, from the spinal cord to the cerebral cortex.

The spinal cord circuits are sufficient for the antigravity support but not for the automatic balance responses (Macpherson & Horak, 2013). The information processing in the spinal cord is the fastest and least flexible among all neural control structures involved in postural control (Taube & Gollhofer, 2010). Postural control through the spinal cord is mostly accomplished via stretch reflexes, reciprocal inhibition, non-reciprocal inhibition and flexion reflexes. Particularly for the static steady-state balance, stretch reflexes and non-reciprocal inhibition (Ib inhibition) are essential (Takakusaki, 2017).

The brain stem is connected to the spinal cord and is thought to play an important role in postural control based on animal experiments (Taube & Gollhofer, 2010). Previous studies revealed that mammals can compensate for perturbations by using their spinal cord and brain stem even though the connections to higher neural centers were destroyed (Sherrington, 1907). Furthermore, the inhibition of brain stem activity resulted in the suppression of postural balance adjustments (Vinay et al., 2005).

The cerebellum, together with the brain stem, is thought to produce automatic balance responses. The brain stem and cerebellum are highly interconnected and work together to integrate somatosensory inputs for balance (Macpherson & Horak, 2013). Based on the clinical observations, it was suggested that the cerebellum plays an essential role in the selection and memorization of compensatory reactions in a situation-specific way.

The cerebral cortex is thought to be involved in both anticipatory and compensatory postural reactions but has more control over anticipatory postural adjustments than compensatory ones. Most voluntary movements are initiated in the cerebral cortex. Albeit the roles of specific areas of cerebral cortex in postural control are not clearly known, it is known that the cortex plays an important role in learning complex postural strategies (e.g., when dancers learn new skills requiring high-balance performance) (Macpherson & Horak, 2013).

2.1.5 Balance strategies in postural control

One of the important parameters regarding balance is the CoM. It is defined as the point equivalent of the total body mass with respect to the global coordinates and calculated as the weighted average of the CoM of each body segment in the three-dimensional space. For the maintenance of balance, the CNS must control the position and the movement of the body's CoM as well as the body's rotation around its CoM (Winter, 1995; Macpherson & Horak, 2013).

During standing, the human body is often modeled as an inverted pendulum (Hof, 2008; Lafond et al., 2004; Mergner et al., 2003; Milton et al., 2009; Shumway-Cook & Woollacott, 2017). On this basis, two main balance recovery strategies have been proposed: (1) Fixed-support in which CoM is maintained over the BoS (Figure 2.2a-b), and (2) change-in-support (Figure 2.2c) in which the BoS is changed to capture the CoM (Winter, 1995). Depending on the current conditions, the CNS switches between these control strategies (Shumway-Cook & Woollacott, 2017).

Fixed-support balance recovery strategies comprise two fundamental strategies. The first one is the ankle strategy (Figure 2.2a) in which the body is modeled as a single-segment inverted pendulum and moves at the ankle (Runge et al., 1999). It is basically in use while standing on a firm support surface. The second one is the hip strategy (Figure 2.2b) in which the body is modeled as a double-segment pendulum and moves both at the ankle and hip. The hip strategy is preferred when the effectiveness of the ankle movement is limited (e.g., standing on a narrow beam) (Horak et al., 1990; Runge et al., 1999). Even though it was shown that the inverted pendulum motion shows high correlations with the human motion in quiet standing (Gage et al., 2004), when the task becomes more complex, the necessity for better models emerges.

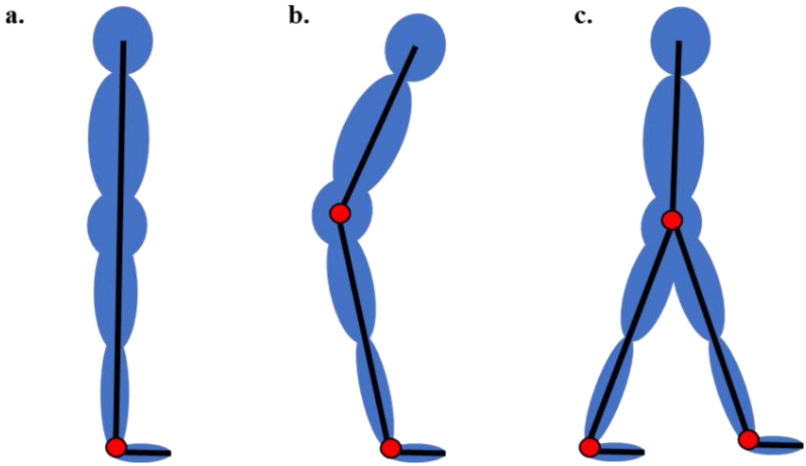

Figure 2.2: Balance strategies: a. Fixed-support with ankle strategy modeled as a single-segment inverted pendulum; b. Fixed-support with hip strategy modeled as a double-segment pendulum; c. Change-in-support strategy with moving base of support.

2.1.6 CNS uses synergies to execute balance strategies in postural control

During movement control, the CNS has to coordinate a redundant musculoskeletal system (Bernstein, 1967) consisting of more degrees of freedom than necessary to complete the given task (Latash et al., 2002). Various approaches have been suggested to explain the CNS deals with this redundancy, such as motor programs (R. A. Schmidt et al., 2018), optimal control (Todorov & Jordan, 2002) or synergies (D'Avella et al., 2003; Latash et al., 2007). Latash et al. (2007) define "synergy" as a neural organization consisting of a multi-element system with elemental variables (EVs) and a performance variable (PV). Two fundamental features of synergy are: (1) the organization of task sharing among the EVs, and (2) the stabilization of the PV by use of the co-variation among EVs. In the redundant musculoskeletal system, different combinations of EVs may result in the same PV (i.e. equivalent movement solutions). This co-varied movement solution space provides flexibility for the control of movements. In this context, redundancy is not seen as a problem but it is an advantage for the CNS, which is also known as the "motor abundance principle" (Gelfand & Latash, 1998). One of the possibilities to assess the equivalent movement solutions is the so-called "uncontrolled manifold (UCM)" approach. Within this approach, a model is needed in which the changes in the EVs are related to the changes in the PV. Ultimately, the effects of the co-varied movement of EVs on the PV are analyzed (Scholz

& Schöner, 2014). According to the UCM approach, EV space is divided into two orthogonal subspaces. One subspace, that is $\mathrm{UCM}_{\parallel}$, consists of all EV configurations that result in the same PV (Scholz & Schöner, 1999). The term UCM refers that the elements are less controlled as long as they lie in this parallel space (Latash et al., 2002). In other words, the motor control system allows the EVs to show high variability as long as the desired value of the PV is obtained. On the other hand, the solutions lying orthogonal to the UCM ($\mathrm{UCM}_{\perp}$) are controlled by the motor control system because the co-variation of EVs in this subspace results in a changed PV value.

In Figure 2.3, the UCM approach is schematically explained with a three-bar linkage system with one fixed target. Figure 2.3a shows the three EVs, these are the three bars connected with the three black joints each with one degree of freedom (i.e. rotation around the joint), and one PV, which is the red target. Thereby, the aim is to hit with the yellow ball this red target. In Figure 2.3b and Figure 2.3c, the illustrative solutions in $\mathrm{UCM}_{\parallel}$ and $\mathrm{UCM}_{\perp}$ subspaces are shown, respectively. In the solution subspace lying parallel to the UCM (i.e. $\mathrm{UCM}_{\parallel}$), the co-variation of the EVs results in a non-changed PV, whereas in the orthogonal solution subspace (i.e. $\mathrm{UCM}_{\perp}$), PV changes with the co-varying movement of the EVs.

2.1.7 Influencing factors on postural control

Balance can be influenced by many factors such as age (M. Henry & Baudry, 2019; van den Bogaart et al., 2022), neurological diseases (Delafontaine et al., 2020), training (Keller et al., 2012; Ringhof et al., 2018; Sherrington et al., 2008, 2020; Taube & Gollhofer, 2010), dual-task situation (Andersson et al., 2002; Wachholz et al., 2020), mood states and anxiety levels (Bolmont et al., 2002; Cuccia & Caradonna, 2009; Wada et al., 2001), head and neck orientation (Park et al., 2012; Szczygieł et al., 2016) as well as craniomandibular system (Julià-Sánchez et al., 2015; Sforza et al., 2006; Treffel et al., 2016). In the following passages, these effects are briefly introduced.

2.1.7.1 Age effects

Falls and fall-related injuries are some of the most important problems, especially for older people (Dionyssiotis, 2012). The risk of falls increases with age due to reduced reaction time and impaired movement strategies (Lizama et al., 2014; Maki & Mcilroy, 1999). Further, the variability structure was also shown to be different in older people. Particularly, it was been suggested that older people have reduced flexibility in controlling multiple joints during recovery from balance perturbations (Hsu et al., 2013).

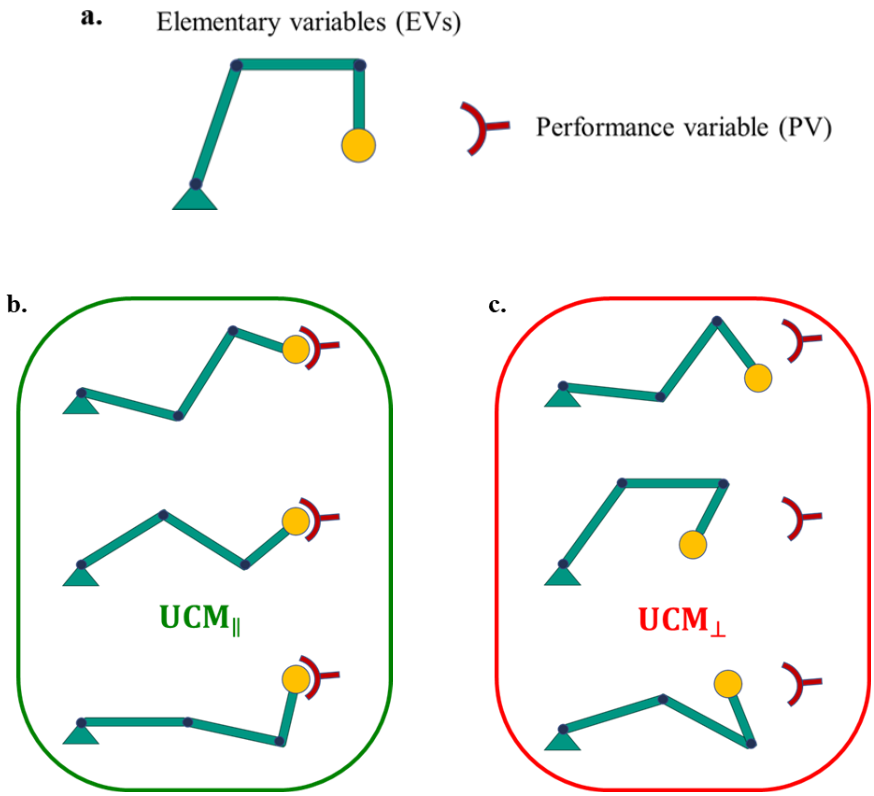

Figure 2.3: Uncontrolled Manifold (UCM) approach. a. Schematic design showing three elementary variables and a performance variable; b. $\mathbf{UCM}_{\parallel}$ subspace includes solutions in which desired PV is achieved; c. $\mathbf{UCM}_{\perp}$ subspace includes solutions in which desired PV is not achieved.

2.1.7.2 Neurological disease effects

Different neurological diseases were shown to reduce the ability to cope with balance perturbations (Karamanidis et al., 2020; Rubenstein, 2006; Takakusaki, 2017). For example, it was shown that Parkinson's patients have difficulties in increasing their BoS after perturbations during walking (Moreno Catalá et al., 2016). Similarly, stroke patients fall more frequently after surface perturbations compared to their age-matched healthy control group and have poorer control during recovery (Salot et al., 2016).

2.1.7.3 Training effects

It was shown that neuromechanical adaptations occur at different sites of the CNS after balance training, and the plasticity of the spinal, corticospinal and cortical pathways are highly task-specific (Keller et al., 2012; Ruffieux et al., 2017; Taube & Gollhofer, 2010; Taube et al., 2008; Zech et al., 2010). Balance training was shown to have positive effects on motor performance, particularly on postural control, jumping ability and strength (Gruber et al., 2007; Taube et al., 2008). On this basis, it is traditionally recommended to improve sports performance (Zech et al., 2010), to augment the rehabilitation process (McKeon & Hertel, 2008) as well as to decrease the risk of falls (Gauchard et al., 1999). However, previous studies showed that balance training improves balance in a task-specific way and the transfer between different balance tasks is very limited (Giboin et al., 2015, 2019; Kümmel et al., 2016; Ringhof & Stein, 2018). Therefore, the effectiveness and benefits of generic balance training are questioned.

2.1.7.4 Dual-task situation effects

It was shown that simultaneously performing additional motor tasks can improve the performance on the secondary balance task. Based on the general motor control and learning literature (e.g., Schmidt et al., 2018), it is assumed that performance diminishes in one or both tasks when these two tasks are performed simultaneously, which can be attributed to the limited attention capacity (Woollacott & Shumway-Cook, 2002). However, previous literature indicated that the postural control may not necessarily show this feature but the performance of a balance task with a secondary task may actually improve performance compared to a single-task condition (Broglio et al., 2005). This special phenomenon in the case of postural control was suggested to be associated with the altered attention and increased automatization of postural control processes (Andersson et al., 2002; Wachholz et al., 2020). However, it should be noted that a secondary task may not necessarily enhance the performance in the executed tasks but can also result in no change (Choi et al., 2023) as well as a decrease in performance. The adverse effects can be attributed to the parallel sharing of a limited set of resources (R. A. Schmidt et al., 2018). Nevertheless, various studies indicated dual-task benefits regarding postural control (Andersson et al., 2002; Broglio et al., 2005; Polskaia et al., 2015; Swan et al., 2004).

2.1.7.5 Mood and anxiety effects

Anxiety can be defined as an over-aroused state that prepares the body to react mentally and physically to potentially dangerous situations (Hoehn-Saric & McLeod, 2000). Anxiety was shown to affect balance in various studies (Bolmont et al., 2002; Cuccia & Caradonna, 2009; Wada et al., 2001). Particularly, changes in sensory organization were detected in case of an altered mood or increased anxiety.

2.1.7.6 Head and neck orientation effects

The changes in the head and neck orientation were shown to affect balance (Park et al., 2012; Szczygieł et al., 2016). Head constitutes about 8% of the average human body weight (Park et al., 2012). Therefore, rapid changes in the head's orientation may disturb balance and require compensatory movements. Further, the head movements lead to alterations of sensory information from visual and vestibular receptors as well as their integrations (Bove et al., 2009).

2.1.7.7 Craniomandibular system effects

Among others, the effects of the craniomandibular system on balance and its control were shown in a number of studies (e.g., Bracco et al., 2004; Cuccia & Caradonna, 2009; Hegab, 2015; Julià-Sánchez et al., 2020; Solovykh et al., 2012; Tardieu et al., 2009). In the following sections, the craniomandibular system, its neuronal connections to the rest of the body, its basic functions as well as its effects on postural control are explained in detail.

2.2 Craniomandibular system

The stomatognathic system comprises a complex set of orofacial structures that are linked by the sensorimotor neural connections peripheral to the CNS, and the craniomandibular system is a fundamental part of the stomatognathic system (Cuccia & Caradonna, 2009; Munhoz & Marques, 2009). The craniomandibular system includes the temporomandibular joints (TMJ), masticatory muscles with the ligaments around them as well as the neural structures (Munhoz & Marques, 2009). The basic functions of the craniomandibular system are to change and to maintain the mandibular position. Any failure in these functions is mostly a part of the so-called temporomandibular disorders (TMD), which can be defined as the pathologies affecting the TMJ or the jaw muscles, or both (Manfredini et al., 2011; McNeill, 1997).

2.2.1 Neuronal connections of craniomandibular system

The nervous system and the stomatognatic system are shown to be anatomically close in proximity. Therefore, these two systems easily interact with each other (Wu et al., 2023). For example, an abnormality of the neurological function can lead to symptoms occurring in the stomatognatic system, such as facial paralysis (Tischfield et al., 2010) and salivation (Newall et al., 1996). Conversely, the symptoms in the stomatognatic system may affect the nervous system (De Wijer et al., 1996; Wu et al., 2023).

The nervous system consists of the CNS and the peripheral nervous system (PNS). The CNS comprises basically the brain and spinal cord, whereas the PNS comprises cranial and spinal nerves (Nowinski, 2017). The 6 of the 12 cranial nerves are associated with the stomatognathic system. These are (1) the trigeminal nerve which is responsible for face sensation and mastication; (2) the facial nerve which is responsible for face movement and taste; (3) the glossopharyngeal nerve which is responsible for taste and swallowing; (4) vagus nerve which is responsible for movement, sensation and abdominal organs; (5) the accessory nerve which is responsible for neck movement; and (6) hypoglossal nerve which is responsible for the muscles of the tongue (Romano et al., 2019; Shoja et al., 2014; Snyder & Bartoshuk, 2016; Sonne & Lopez-Ojeda, 2022; Wu et al., 2023).

2.2.2 Jaw movement and its control

The jaw is moved by the jaw muscles in a complex three-dimensional manner. The jaw muscles can be allocated into two groups depending on whether their contraction closes or opens to jaws. Basically, there are three jaw-closing muscles (masseter, temporalis, and medial pterygoid) and two jaw-opening muscles (lateral pterygoid and digastric) (Murray, 2016).

The movements of the jaws can be classified as voluntary, reflexive and rhythmical jaw movements. These are generated by the participation of many parts of the CNS (Murray, 2016). Voluntary jaw movements, such as opening, closing, protrusive and lateral jaw movements, are initiated from the cerebral cortex and passed on to the face motor cortex. Whereas, reflexive jaw movements demonstrate pathways that contribute to the refinement of the movements, and can be used by the higher motor centers for the generation of more complex movements. Finally, the rhythmical movements, such as mastication or chewing, are controlled by a central pattern generator in the brainstem. During mastication, the muscles of the tongue help in maneuvering the food bolus in the mouth, whereas the muscles of the lip and cheek help to keep the food bolus within the mouth on the occlusal table (Sessle et al., 2013).

Jaw clenching is a task in which mainly the jaw-closing muscles, especially the masseter, are active (D'Amico et al., 2013). Thereby, the forces are generated by a complex co-activation of muscles involved in masticatory (Schindler et al., 2007). In the normal resting position of the craniomandibular system, the teeth do not have sustained contact. On this basis, a continuous act of jaw clenching (synonymously used also as “teeth clenching” (e.g., de Souza et al., 2021; Hellmann et al., 2011a; Iida et al., 2010)) can be seen as an abnormal parafunctional habit. Furthermore, jaw clenching is assumed to be a risk factor for TMD (Magnusson et al., 2005; Velly et al., 2003). For example, bruxism, which is characterized by grinding and clenching of the teeth (Lobbezoo et al., 2006), was also reported to be a risk factor for neck pain (Lavigne et al., 2001; Testa et al., 2017) as well as for the displacement of discs (Michelotti et al., 2010).

In the case of bruxism, the jaw-closing muscles are involuntarily activated both during sleep as well as during wakefulness (Lobbezoo et al., 2018). Even though various studies describe it as a disorder (e.g., Lobbezoo et al., 2006; Manfredini et al., 2013), according to the international consensus published in 2018 “in otherwise healthy individuals, bruxism should not be considered as a disorder but rather as a behavior that can be a risk (and/or protective) factor for certain clinical consequences.” (Lobbezoo et al., 2018). Furthermore, observational studies reported that increased masseter activity may occur as an unconscious habit for example in case of initial accelerations during track and field activities (Nukaga et al., 2016) or landing (Nakamura et al., 2017). On this basis, the question came up if the jaw clenching can aid in performing sports or daily activities.

Over the years, jaw clenching has gained attention due to its potential beneficial effects during sports activities (Ringhof, Hellmann, et al., 2015), such as counter movement jump (Ebben et al., 2008) or strength training (de Souza et al., 2021) as well as for balance (Hellmann, 2011a, 2015). On the other hand, there are still conflicting results regarding its impact (Forgione et al., 1992; Ringhof et al., 2016) suggesting that the effects of jaw clenching are limited to certain conditions. Furthermore, not only the changes in the activities (e.g., jaw clenching (Hellmann et al., 2011; Tomita et al., 2021)) but also the relative position of the cranomandibular system elements to each other (e.g., dental occlusion (Bracco et al., 2004; Julià-Sánchez et al., 2015; Sakaguchi et al., 2007)) were shown to be able to affect the human postural system. In the following chapter, the effects of the craniomandibular system on postural control are introduced and explained in more detail.

2.3 Craniomandibular system and postural control

The craniomandibular system is suggested to be a close component of the upper body (Khan et al., 2013). Over the years, a lot of research was conducted to investigate the relationship between the postural control and the craniomandibular systems as well as the clinical impacts (e.g., Cuccia & Caradonna, 2009; Nowak et al., 2023; Sakaguchi et al., 2007; Solovykh et al., 2012). Various changes in the position or in the activities of the craniomandibular system were shown to affect the body posture and its control (e.g., Alghadir et al., 2015a, 2015b, 2015c; Gangloff et al., 2000; Hegab, 2015; Khan et al., 2013; Kushiro & Goto, 2011; Munhoz & Marques, 2009; Sakaguchi et al., 2007; Treffel et al., 2016). However, it should also be noted that not all previous studies support the relationship between the postural control and craniomandibular systems (e.g., Ferrario et al., 1996; Alghadir et al., 2022).

Based on the current state of research, the effects of the change in positions and activities of the craniomandibular system are explained in more detail in the following two sections, respectively. Even though there is not yet a clear finding showing directly why the craniomandibular system may affect the postural control, there are possible mechanisms to explain these effects, which are introduced in more detail in Section 2.3.3.

2.3.1 Change in positions of craniomandibular system

Changes in the mandibular positions may lead to changes in the body posture (Cuccia & Caradonna, 2009; Huggare & Raustia, 1992; Sakaguchi et al., 2007; Tardieu et al., 2009). Conversely, the changes in the body posture may result in a changed mandibular position (Khan et al., 2013; Lund et al., 1970; Tingey et al., 2001) as well as in a changed chewing behavior (Iizumi et al., 2017).

The studies comprising the effects of the mandibular positions on balance mostly investigate the changes in the occlusion. The term “occlusion” can simply be defined as the contact between the teeth (J. R. Clark & Evans, 2001; Davies & Gray, 2001; Hassan & Rahimah, 2007). The occlusion can be further categorized as static occlusion and dynamic or functional occlusion. Static occlusion refers to the teeth contact when the mandible is closed and in a static condition (J. R. Clark & Evans, 2001; Davies & Gray, 2001), whereas dynamic occlusion indicates the contact between teeth when the mandible moves relative to the maxilla (Davies & Gray, 2001) or during functional tasks (J. R. Clark & Evans, 2001). The studies comprising the occlusion effects on the balance refer mostly to static occlusion (Bracco et al., 1998; Gangloff et al., 2000; Julià-Sánchez et al., 2015, 2020; Michelotti et al., 2011; Nowak et al., 2023; Sakaguchi et al., 2007; Tardieu et al., 2009). However, even if it is very rare, the term “occlusion” can also be used as a synonym for “jaw clenching” (Hosoda et al., 2007). In this thesis, the term “jaw clenching” will be preferred over “occlusion” if the term “occlusion” is used to refer to “jaw clenching”.

In various studies, the influences of static occlusion on balance were shown (Bracco et al., 1998; Gangloff et al., 2000; Julià-Sánchez et al., 2015, 2020; Sakaguchi et al., 2007; Tardieu et al., 2009). In a pilot study published in 1998, it was shown that the alterations in the mandibular positions can influence posture (Bracco et al., 1998). In another study analyzing different mandibular positions imposed by interocclusal splints, it was found that dental occlusion may influence the static steady-state balance (Gangloff et al., 2000). Similarly, Sakaguchi et al. (2007) analyzed the relationship between the mandibular positions and body posture. The authors showed that changes in mandibular position may affect the posture and conversely, the changes in posture may affect the mandibular positions. Julià-Sánchez et al. focused in their various studies on the effects of dental occlusion on balance, particularly in unstable or dynamic conditions (Julià-Sánchez 2015, 2016, 2019, 2020). They concluded that (1) dental occlusion may affect balance in unstable and dynamic conditions but not in stable conditions (Julià-Sánchez et al., 2015, 2020), (2) when more difficult conditions for postural control (e.g., unstable conditions, external perturbations or fatigue) are present, the sensory information linked to the dental occlusion comes more strongly into effect (Julià-Sánchez et al., 2016, 2019). Similarly, Tardieu et al. (2009) investigated the effects of dental occlusion for static and dynamic balance with eyes open as well as eyes closed conditions. The authors found that steady-state balance was influenced by dental occlusion in dynamic conditions and in the absence of visual information. Based on their findings, they suggested that the sensory information associated with the dental occlusion becomes relevant when the balance task is challenging, and its importance grows as the other sensory cues become scarce.

Besides the studies focusing on dental occlusion, there are also studies investigating the malocclusion effects on balance. In a previous study, it was reported that the participants with anterio-posterior malocclusion showed worse static steady-state balance (Nowak et al., 2023). On the other hand, there are also studies suggesting no effect of occlusion on balance. In an overview study focusing on the relationship between dental occlusion and posture (Michelotti et al., 2011), the authors suggested not to perform occlusal or orthodontic treatment in order to treat or prevent postural imbalances. In another study analyzing the effects of static and dynamic occlusion on balance among people with blindness, it was suggested that the alterations in static and dynamic jaw positions do not influence static steady-state balance (Alghadir et al., 2022). However, it should be noted that the studies suggesting no effects of dental occlusion on balance focused on static steady-state balance and did not investigate the effects on dynamic balance.

Besides the occlusion-related research, there are also studies that focused on the changes in the tongue position (Alghadir et al., 2015a; Russo et al., 2020). Alghadir et al. (2015a) investigated the effects of deliberately changed tongue position on the static steady-state balance during quiet standing on an unstable surface with closed eyes. Compared with the habitual jaw position, tongue positioning against the upper incisors enhanced the balance in static steady-state conditions. On the other hand, Russo et al. (2020) compared three different tongue positions in static steady-state conditions but with open eyes. The authors did not detect any significant differences between different tongue positions in terms of static steady-state balance performance. However, it should be noted that Alghadir et al. (2015a) used the velocity of the center of gravity to operationalize the static steady-state balance, whereas Russo et al. (2020) used the sway of the CoP.

2.3.2 Change in activities of craniomandibular system

Change in the activities of the craniomandibular system was shown to influence the postural control system, such as chewing (Alghadir et al., 2015b; Kushiro & Goto, 2011) or jaw clenching (Alghadir et al., 2015c; Hellmann et al., 2011a; Nakamura et al., 2017; Ringhof, Leibold, et al., 2015; Tanaka et al., 2006; Tomita et al., 2021; Treffel et al., 2016).

2.3.2.1 Chewing

Chewing is a part of daily activities for healthy people since it is used to break down food within a series of movements. Chewing cycles are semiautomatic motor behavior and involve well-trained muscles (Hellmann et al., 2011a; Lund, 1991). Kushiro and Goto (2011) analyzed the effects of chewing gum on the static steady-state balance and found that CoP stability increased during the mastication of chewing gum. On the other hand, in another study analyzing the changes in body oscillations during unilateral chewing of a rubber cube and maximum jaw clenching, no effects of these jaw motor tasks on body sway could be detected (Hellmann et al., 2011a).

2.3.2.2 Jaw clenching

To date, there are several types of research investigating jaw clenching effects on postural control. The first experiment addressing this issue was published at the end of the 20th century. Ferrario et al. (1996) investigated the effects of maximum jaw clenching in centric occlusion as well as on two cotton rolls and reported no effects of jaw clenching on static steady-state balance. Four years later, Takada et al. (2000) showed that voluntary jaw clenching may contribute to the facilitation of lower limb muscles through enhanced H-reflex, which may improve the stability of the movements. However, they did not assess the static steady-state balance performance. Sforza et al. (2006) conducted a pilot study with male astronauts to find out if the effects of maximum jaw clenching differ when it is performed on a splint compared to without a splint condition. They reported that a functionally more symmetric mandibular position resulted in a more symmetric sternocleidomastoid muscle contraction pattern as well as less body sway. In another study by Hosoda et al. (2007), it was investigated if jaw clenching with 50% of the maximum voluntary contraction (MVC) of the masseter muscle may affect the latency of the center of gravity movement initiation after external perturbations (i.e. dynamic reactive balance). It was reported that the greater the external perturbation the shorter the latency in jaw clenching conditions, whereas in non-clenching conditions, the latency increased with increasing external perturbation. In the same year, Tanaka et al. (2006) published a paper analyzing the influence of jaw clenching with 50% and 100% MVCs on head movement and body sway after an external perturbation generated by a striking 3 kg weight. They found that jaw clenching leads to less head movement as well as to less body sway after the impact, and suggested that jaw clenching with a 50% MVC was more suitable than the maximum jaw clenching condition in terms of stabilizing effects.

After 2010, the relationship between jaw clenching and postural control gained more attention as a research topic (Alghadir et al., 2015c; Hellmann et al., 2011a, 2012, 2015; Nakamura et al., 2017; Ringhof et al., 2016; Ringhof, Stein, et al., 2015; Tomita et al., 2021; Treffel et al., 2016). Hellmann et al. (2011a) analyzed the effects of a series of jaw motor tasks on the CoP displacements during upright standing. These jaw motor tasks included jaw clenching at submaximal forces of 50 to 300 N, maximal jaw clenching unilateral and bilateral as well as unilateral chewing. Compared with the mandibular rest positions, submaximal jaw clenching led to significant reductions in body sway, as evidenced by a smaller area of the CoP confidence ellipses, whereas unilateral chewing and maximal jaw clenching tasks did not alter body sway. The subsequent studies specifically focused on submaximal jaw clenching rather than maximal jaw clenching (Hellmann et al., 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015). Ringhof, Stein, et al. (2015) found that CoP sway area, as well as CoP path lengths, were significantly reduced during jaw clenching compared to the open-mouth, non-clenching control conditions for both bipedal narrow stance and unipedal stance on dominant and non-dominant legs. In a follow-up study (Hellmann et al., 2015), lower limb joint angles as well as muscle co-contractions were analyzed. Submaximal jaw clenching and non-clenching conditions did not show any significant differences for the mean values of the lower limb joint angles, whereas standard deviations were significantly lower during submaximal jaw clenching. Furthermore, reductions in the joint ROMs and angular velocities as well as in the co-contraction ratios were detected for the submaximal jaw clenching condition. The authors concluded that submaximal jaw clenching influences muscular co-contraction patterns which result in enhanced kinematic precision. In a further experiment by Ringhof, Leibold, et al. (2015), it was examined if the clenching of the fist would also lead to similar reductions in COP sway. The findings of the study revealed that both jaw clenching and fist clenching result in reduced COP displacements, and the two conditions did not differ significantly from each other. It was suggested that concurrent muscle activation significantly improves static steady-state balance possibly by facilitation of human motor excitability. Michalakis et al. (2019), investigated how body weight distribution changes during concurrent maximum jaw clenching as well as during asymmetrical jaw clenching (with 1 mm disocclusion on the right and left sides). They reported that jaw clenching and occlusional stability may lead to a medio-lateral shift of the weight distribution but not to anterio-posterior shifts. One of the key findings of the study was that the participants shifted their body weight opposite to the jaw clenching side. The authors suggested that this phenomenon occurs to prevent falling. Based on the theory of Yoshino et al. (2003), they argumented that the participants tend to change the head position towards the jaw clenching side, consequently, the weight distribution of the upper body and the lower limbs shifted towards the opposing side of the jaw clenching side in order to compensate the shifted head position.

Besides the various studies analyzing the jaw clenching effects on static steady-state balance, it was also investigated in a few studies how jaw clenching affects dynamic balance (Nakamura et al., 2017; Ringhof et al., 2016). In a pilot study analyzing the jaw clenching effects on landing after a jump (Nakamura et al., 2017), jaw clenching effects on dynamic balance during landing were found to be limited. However, the jaw clenching task was not constrained to a force level but it was reported to be at least 20% of maximum jaw clenching and increased up to nearly 400%. In another study conducted by Ringhof et al. (2016), the effects of submaximal jaw clenching on dynamic postural stability and joint kinematics during balance recovery after forward loss of balance compared with non-clenching condition were investigated. The authors found no effects of submaximal jaw clenching on balance recovery and lower limb joint kinematics, which was in contrast to their findings regarding the stabilizing effects of submaximal jaw clenching during upright standing (Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015). They attributed this to the different control strategies used for static steady-state balance and balance recovery after simulated forward falls. Further, they argued that reductions in CoP displacement –which leads to enhanced static steady-state balance– would not necessarily improve the balance under dynamic conditions but even may degrade it. Finally, they suggested that future studies should investigate the submaximal jaw clenching effects on dynamic reactive balance after unexpected perturbations as well as compared with open mouth and habitual conditions.

2.3.3 Possible mechanisms of craniomandibular system effects on postural control

Although the exact mechanisms are still unknown, the contribution of the functional status of the stomatognathic system in the postural balance was shown to be about 2% (Solovykh et al., 2012). There are several approaches that try to explain why and how the stomatognathic system has an influence on posture and its control.

One essential explanation is that the trigeminal nerve plays a key role in the connection between the stomatognathic system and the postural control system. The trigeminal nerve is neuroanatomical connected to the several structures associated with postural control. The mandibular nerve, which innervates the masseter muscle together with the other masticatory muscles, is one of the three branches of the trigeminal nerve (Buisseret-Delmas et al., 1999; Julià-Sánchez et al., 2015; Paya-Argoud et al., 2019). Furthermore, in the morphological studies, it was shown that the vestibular nuclear complex and the spinal trigeminal nuclei are connected in rats (Devoize et al., 2010; Ruggiero et al., 1981).

Subsequent investigation regarding the influences of the craniomandibular system was the modulation of reflexes (Boroojerdi et al., 2000; Miyahara et al., 1996; Takada et al., 2000; Tuncer et al., 2007). In the late 1800s, Erno Jendrassik conducted groundbreaking research on voluntary jaw clenching and its neuromechanical effects. He discovered that in patients with neurological impairments, jaw clenching and pulling apart flexed and hooked fingers may enhance lower limb reflexes (Jendrassik, 1885). This effect was named after him and known as “the Jendrassik maneuver”. Various studies reported that the Jendrassik maneuver has potentiating effects on the reflexes as well as on the motor-evoked potentials of the upper and lower body muscles (Bussel et al., 1978; Delwaide & Toulouse, 1981; Dowman & Wolpaw, 1988; Gregory et al., 2001; Sugawara & Kasai, 2002; Zehr & Stein, 1999). Similar to the Jendrassik maneuver, jaw clenching is used commonly to enhance the Hoffmann (H)-reflex and motor-evoked potentials of both lower and upper limb muscles (Boroojerdi et al., 2000; de Souza et al., 2021; Miyahara et al., 1996; Tuncer et al., 2007).

The H-reflex, which is a component of the stretch reflex, was first identified by Hoffmann (1918). Hoffman discovered a reflex reaction in the calf muscles that occurred after stimulation of the posterior tibial nerve, and he showed that its latency response was equivalent to the Achilles reflex (Fisher, 2012). By use of H-Reflex, the alpha motoneuron excitability can be estimated and nervous system responses to several neuromechanical conditions can be assessed. It is one of the most frequently used tools for investigating electrophysiological alterations at the spinal level and activates motor units recruited monosynaptically via the afferent pathway (Grosprêtre & Martin, 2012; Misiaszek, 2003; Tuncer et al., 2007). Various studies showed that the H-reflex can be facilitated through voluntary jaw clenching (de Souza et al., 2021; Mitsuyama et al., 2017; Miyahara et al., 1996; Takada et al., 2000; T. Takahashi et al., 2003; Tuncer et al., 2007; Yamanaka et al., 2000). Through voluntary jaw clenching, the area representing the face in the motor cortex is activated. This could spread to the other areas of the motor cortex representing the upper and lower extremities (Boroojerdi et al., 2000). Increased excitability in the motor system during both preparation and execution of jaw clenching motor task was shown in various studies (Komeilipoor et al., 2017; Sugawara et al., 2005; M. Takahashi et al., 2006).

Another explanation for the jaw clenching effects on postural control may be the dual-task paradigm. Generally, when two tasks are performed concurrently, performance in one or both tasks diminishes (R. A. Schmidt et al., 2018). This phenomenon can be explained by the restricted attention capacity (Woollacott & Shumway-Cook, 2002). In the case of postural control, however, past research has shown that integrating a secondary task with a balance task may actually improve performance when compared with a single task condition (e.g., Broglio et al., 2005). Changes in attention and greater automatization of postural control processes can explain this effect (Andersson et al., 2002; Wachholz et al., 2020). On this basis, it may be argued that concurrent jaw clenching, as a secondary novel task, has enhancing effects on postural control. Therefore, it is essential to understand if these effects are related to dual-task benefits or specifically to neuromechanical effects caused by concurrent jaw clenching.

3 Aims and Scope of this Thesis

As introduced in more detail in Section 2.3, changes in the craniomandibular system were shown to influence the postural control system, for example through dental occlusion or concurrent clenching of the jaw. Previous studies indicated that when more difficult conditions regarding postural control are present (e.g., unstable or challenging tasks, external perturbations, or fatigue), the sensory information associated with dental occlusion comes more strongly into play (Julià-Sánchez et al., 2016, 2019; Tardieu et al., 2009). On this basis, it can be argued that the effects associated with the activities of the craniomandibular system, such as jaw clenching, may also become more important during dynamic or challenging balance tasks.

The influences of concurrent jaw clenching on static steady-state balance have been investigated in various studies (e.g., Hellmann et al., 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015) but its effects on balance under dynamic conditions have not yet been considered in detail (Nakamura et al., 2017; Ringhof et al., 2016). Since the effects observed during one balance task may not always be transferable to another (Giboin et al., 2015; Kümmel et al., 2016; Ringhof & Stein, 2018), the question arises if the influences of concurrent jaw clenching shown during static steady-state balance tasks would also be observed during dynamic balance tasks. In addition, dynamic balance was suggested to be more related to the risk of falling than static balance (Rubenstein, 2006). Therefore, understanding balance under dynamic conditions may reveal important findings regarding fall prevention as well as rehabilitation. In this thesis, it was focused on the two sub-categories of dynamic balance, these are dynamic reactive balance and dynamic steady-state balance, under the influence of jaw clenching.

The next five chapters (Chapter 4-8) contain five research articles. Chapter 4-6 contain articles on jaw clenching effects on dynamic reactive balance, whereas, the following two chapters (Chapter 7-8) focused on dynamic steady-state balance.

The research comprised within this thesis consisted of two main experiments. In the first experiment, it was focused mainly on the influences of jaw clenching on dynamic reactive balance, whereas in the second experiment, the jaw clenching effects on dynamic steady-state was investigated. All of the measurements were carried out at the BioMotion Center of the Institute of Sports and Sports Science (IfSS) at Karlsruhe Institute of Technology (KIT) between 2019-2022. All of the papers were published in international peer-reviewed journals between 2022-2024. The research was supported by the German Research Foundation (Grant numbers: STE 2093/4-1 and HE 6961/3-1; STE 2093/4-3 and SCHM 2456/6-3) and conducted in collaboration with the Department of Prosthodontics at the University of Würzburg, the Department of Sport and Sport Science at the University of Freiburg, the Department of Diagnostic and Interventional Radiology at the University of Freiburg and the Dental Academy for Continuing Professional Development in Karlsruhe.

3.1 Influence of jaw clenching on dynamic reactive balance

As explained in more detail in Section 2.1.1, dynamic balance refers to postural control either in advance of or in response to internal and external perturbations, as opposed to static balance which deals with postural control under unperturbed conditions (Shumway-Cook & Woollacott, 2017). Dynamic balance is essential for maintaining balance in daily life, for example during walking or standing on a train that suddenly accelerates. Another important point is that most falls occur under dynamic conditions, e.g., stumbling and slipping during walking (Blake et al., 1988; Hiscock et al., 2014). On this basis, it is vital to search for ways to improve dynamic balance. Previous studies showed that concurrent jaw clenching may decrease the body sway and, therefore improve static steady-state balance but its effects during dynamic reactive balance have not yet been discovered.

As introduced in Section 2.1.1, dynamic reactive balance can be defined as the compensation of an unpredicted perturbation. These perturbations es are mostly mechnical perturbations, caused by surface translations and rotations (Lesinski et al., 2015a; Shumway-Cook & Woollacott, 2017). The first experiment of this research aimed at investigating the effects of submaximal jaw clenching on dynamic reactive balance which was assessed by the use of an oscillating platform with unexpected mechanical perturbations. The objectives of the first experiment were first, to find out if submaximal jaw clenching has acute enhancing effects on dynamic reactive balance (Chapter 4); second, to distinguish if the acute effects of jaw clenching were specifically due to neuromechanical effects of this oral-motor task or more generally due to activities of the craniomadibular system, by comparing jaw clenching with tongue pressing condition (Chapter 4); third, to investigate the reflex activities and co-contraction behavior of the trunk and lower limb muscles under the effects of three oral-motor tasks, these are jaw clenching, tongue pressing and habitual stomatognatic behavior (Chapter 5); and fourth, to examine if the effects of jaw clenching were associated with dual-task benefits or specifically due to neuromechanical modulations associated with jaw clenching (Chapter 6). To reach the above-mentioned objectives, a three-armed intervention experiment with 64 participants was carried out whose details are given in the following three chapters (Chapter 4-6).

3.2 Influence of jaw clenching on dynamic steady-state balance

Besides the dynamic reactive balance, another important dynamic balance category is the dynamic steady-state balance, which can be defined as the maintenance of balance after self-initiated perturbations, such as swinging the lower leg to step forward during walking or running (Shumway-Cook & Woollacott, 2017).

The later steady-state phase of the balance task on the oscillating platform from the first experiment was considered in this part of the thesis. Thereby, the research question to be answered was if the sway, control and stability of the CoM during dynamic steady-state balance were affected by the effects of submaximal jaw clenching or tongue pressing compared with habitual stomatognatic behavior condition (Chapter 7).

The second experiment was carried out mainly to address the influences of concurrent submaximal jaw clenching during dynamic steady-state balance which was assessed by use of a stabiliometer. The objective of the second experiment was threefold: first, if concurrent submaximal jaw clenching enhances dynamic steady-state balance; second, if jaw clenching effects persist when this secondary task loses its novelty and the increased attention associated with it; and third, if the better dynamic steady-state balance performance is associated with decreased muscle activities.

4 Study I – Modulation of Postural Control - Dynamic Reactive Balance

Published as

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4.1 Abstract

Background: The influence of the stomatognatic system on human posture control has been investigated under static conditions, but the effects on dynamic balance have not yet been considered. Objective: Investigating the influence of different functional stomatognatic activities (jaw clenching (JAW), tongue pressing (TON) and habitual jaw position (HAB)) on postural performance during a dynamic reactive balance task.

Methods: Forty- eight physically active and healthy adults were assigned to three groups differing in oral- motor tasks (JAW, TON or HAB). Dynamic reactive balance was assessed by an oscillating platform which was externally perturbed in four directions. Performance was quantified by means of Lehr's damping ratio. Mean speeds of the selected anatomical regions (head, trunk, pelvis, knee and foot) were analysed to determine significant performance differences.

Results: The groups differed significantly in balance performance in direction F (i.e. forwards acceleration of the platform). Post-hoc tests revealed that the JAW group had significantly better performance compared with both the HAB and TON groups. Better performance was associated with a decreased mean speed of the analysed anatomical regions.

Conclusion: JAW can improve dynamic reactive balance but the occurrence of positive effects seems to be task- specific and not general. TON seems not to have any observable effects on dynamic reactive balance performance, at least when evaluating it with an oscillating platform. JAW might be a valuable strategy which could possibly reduce the risk of falls in elderly people; however, further investigations are still needed.

4.2 Introduction

Posture control has a vital role in human daily life. It ensures that movements are initiated and executed in an optimal manner both in static and in dynamic conditions (e.g., upright standing and locomotion, respectively) (Shumway-Cook & Woollacott, 2017). It involves controlling the body's position with respect to the environment for the dual purposes of stability and orientation (Shumway-Cook & Woollacott, 2017). Multiple sensory signals from visual, somatosensory and vestibular systems acting on the spinal and supraspinal structures of the central nervous system (CNS) are used to detect and correct instability in posture and to ensure balance (Takakusaki, 2017). Depending on the balance task at hand, the CNS adapts the weighting and thereby the relative importance of sensory signals. Finally, the sensory information must be transformed into motor commands to ensure the body's balance in a task-specific manner. However, the functioning of these underlying postural control mechanisms is not yet fully understood (Peterka, 2002; Shumway-Cook & Woollacott, 2017). Impaired human postural control may lead to a reduced participation in daily life, an increased risk of falls and even to increased mortality risk (Rubenstein, 2006).

The significance of the abovementioned sensory systems shows that postural control may also be influenced by motor activity in the masticatory system (Julià-Sánchez et al., 2020). There are a variety of studies indicating an influence of stomatognatic motor activity in the form of chewing, tongue activity or different clenching conditions in different jaw relations on human balance and posture under static conditions (Alghadir et al., 2015c; Gangloff et al., 2000; Hellmann et al., 2011a, 2015; Julià-Sánchez et al., 2020; Ringhof et al., 2016; Ringhof, Stein, et al., 2015; Sakaguchi et al., 2007). This means, in particular, a reduced body sway in the anterior-posterior direction (Hellmann et al., 2011a), a reduced variability of muscular co-contraction patterns of posture-relevant muscles of the lower extremities and reduced trunk and head sway under the influence of controlled biting activities (Hellmann et al., 2015). This might be interpreted as a body sway stabilizing effect. These facts in conjunction with the observations of an improved responsiveness to auditory and visual stimuli (Garner & Miskimin, 2009), and relevant effects on force development (Forgione et al., 1992) under the influence of biting activities, might be of clinical relevance for the prevention of falls in elderly people. For this group there is evidence for an increased risk of falling resulting from an insufficient dental or prosthetic status (Mochida et al., 2018; Okubo et al., 2010).

There are several possible explanations for the measured effects of masticatory muscle activity on posture control. First, this could be explained by the stimulation of periodontal receptors or by the different proprioceptive input due to different jaw relations that are centrally integrated along with other sensory input (Boroojerdi et al., 2000). It is also conceivable that the motor activity in the masticatory system facilitates the excitability of the human motor system in a manner similar to the Jendrassik manoeuvre (Jendrassik, 1885), which in turn increases the neural drive to the distal muscles (Ebben, 2006; Ebben et al., 2008). A challenge in interpreting the results of these studies is the methodological heterogeneity and the phenomenon of interactions between postural and cognitive tasks, shown in physiological and neurocognitive studies (Fraizer & Mitra, 2008). Therefore, an integrative interpretation of the results appears difficult. However, a variety of neuromechanical interactions, for instance synchronized extension–flexion movements of the head during jaw-opening/closing cycles (Eriksson et al., 2000), substantially increased amplitudes of the human soleus H-reflex during voluntary teeth clenching (Boroojerdi et al., 2000; Miyahara et al., 1996), neck muscle reflex responses triggered by trigeminal stimulation (Abrahams et al., 1993; Alstermark et al., 1992) and co-contractions of the masticatory and neck muscles (G. T. Clark et al., 1993; Giannakopoulos et al., 2018) are also evidence for the close functional integration of the masticatory system in human motor control processes. The neuroanatomical basis for all these phenomena was shown in animal models in the form of numerous neuroanatomical connections of the trigeminal nerve within the brainstem, and projections to all levels of the spinal cord (Contreras et al., 1982; Ruggiero et al., 1981).

As mentioned above, the influence of the masticatory system on human posture control has been investigated under static conditions. The studies showed that oral-motor activities such as jaw clenching may contribute to increased postural stability, represented in terms of decreased postural sway in upright bipedal und unipedal standing (Hellmann et al., 2011a, 2015; Ringhof et al., 2016; Ringhof, Stein, et al., 2015). To the best of our knowledge, the effects of motor activity of the masticatory system on dynamic balance have not yet been investigated in depth (Ringhof et al., 2016).

Therefore, the aim of this study was to investigate the influence of different functional stomatognatic activities on postural performance during a dynamic reactive balance task, which was operationalized with an oscillating platform perturbed in different directions. It was hypothesized that jaw clenching (JAW) and tongue pressing (TON) would influence dynamic reactive balance performance. These changes in task performance were hypothesized to be associated with specific adaptations in the segmental kinematics of the human body. The results of this study may contribute to the understanding of postural control mechanisms, particularly in conjunction with the masticatory system, and might bring up initial hypotheses as to whether masticatory muscle activity might reduce the risk of falls.

4.3 Methods

4.3.1 Participants

Forty-eight physically active adults (25 female, 23 male; age: 23.8 ± 2.5 years; height: 1.73 ± 0.09 m; body mass: 69.2 ± 11.4 kg) participated in the study. Their dominant legs were determined based on self-reports or, in case of uncertainty, by means of test trials on the oscillating platform (Ringhof & Stein, 2018). All participants gave written informed consent prior to the study. They confirmed that they were physically active (participating in any kind of sports regularly, at least 3 times per week), naive to the Posturomed task and had no muscular or neurological diseases. They had also no signs and symptoms of temporomandibular disorders (assessed by means of the RDC/TMD criteria (Manfredini et al., 2011)), and presented with full dentition (except for 3rd molars) in neutral occlusion. The study was approved by the Ethics Committee of the Karlsruhe Institute of Technology.

4.3.2 Experimental procedure

4.3.2.1 Balance tasks

Dynamic reactive balance was assessed by use of an oscillating platform, the Posturomed (Haider-Bioswing, Weiden, Germany). This commercial device consists of a rigid platform (12 kg, 60 cm × 60 cm) and eight 15-cm steel springs of identical strength, and can swing along the horizontal plane in all directions. The Posturomed has previously been used in scientific studies to systematically investigate dynamic reactive balance performance after perturbations (Freyler et al., 2015; Kiss, 2011a). In the present study, an automatic custom-made release system was used to slowly displace the Posturomed horizontally (up to 2.5 cm) in one of the four possible directions: back (B), front (F), left (L), right (R). The directions used here indicate, by convention, the direction to which the platform was accelerated after release (e.g., B indicates that the platform was accelerated backwards after release, which led to anterior body sway relative to the platform).

The perturbations were applied randomly in one of the four directions. The participants' task was to compensate the perturbation as quickly as possible. Before each trial, participants were asked to stand on the platform on their dominant leg, with hands placed at their hips, eyes focusing at a target whose height was adjusted to their eye level in advance and which was horizontally 4 m away from the center of the platform. Trials were considered invalid if participants quitted performing their oral-motor task (JAW and TON), had ground contact with the non-standing foot, changed the placement of their standing foot, released one of the hands from the hip or lost their balance.

4.3.2.2 Group assignment and oral-motor tasks

For the assignment, each of the 48 participants had a familiarization period on the Posturomed consisting of two static trials and two trials with perturbation. Afterwards, a baseline measurement with perturbation and in habitual biting condition was performed to determine the initial balance performance based on Lehr's damping ratio (DR) (Kiss, 2011a). Based on the subjects' baseline performance value and gender, a balanced assignment to the three groups was ensured such that the initial level of performance difference between groups is minimized. The statistical examination by means of a one-way analysis of variance (ANOVA) revealed no baseline performance differences between the three groups ($p = 0.767$). The three groups each consisting of 16 participants had to concurrently fulfil one of the following oral-motor tasks during each trial of the experiment:

- **JAW:** instructed, controlled submaximal jaw clenching - activity of the masticatory muscles during simultaneous occlusal loading,
- **TON:** instructed, controlled submaximal tongue pressing against the palate - stomatognatic muscle activity without occlusal loading,
- **HAB:** habitual stomatognatic behavior - jaw positioning without any instruction.

The respective oral-motor activity was measured by means of EMG recordings (detailed information in the "Data collection" section). As a reference, the JAW group were trained in submaximal jaw clenching at a force of 75 N by use of a RehaBite® (Plastyle GmbH, Uttenreuth, Germany), a medical training device consisting of liquid-filled plastic pads and working based on hydrostatic principles (Giannakopoulos, Rauer, et al., 2018), just before the measurements. During the training, EMG activity was monitored and training ended once the participant achieved a consistent biting force at 75 N (resulting in a mean EMG activity of about 5% maximum voluntary contraction, MVC). The corresponding EMG level of biting activity was used later to determine if the submaximal jaw clenching condition was met during the experiment. During the balance task measurements, the JAW group performed the clenching task on an Aqualizer® intraoral splint (medium volume; Dentrade International, Cologne, Germany). The TON group also received training, which consisted of applying a submaximal force with the tip of the tongue against the anterior hard palate. For TON, the training ended once the participants achieved a consistent EMG activity at 5% of their MVC, measured in the region of m. digastricus venter anterior. For both groups, training for the oral-motor task lasted approximately five minutes. The HAB group did not receive any training or instructions.

4.3.2.3 Data collection

A wireless EMG system (Noraxon, Scottsdale, USA) operating at 2000 Hz was used to measure EMG activity of the masseter for JAW and HAB; and of the suprahyoid muscles of the floor of mouth (FoMM) for TON, measured in the region of the digastricus venter anterior muscle. The skin over the corresponding muscles was carefully shaved, abraded and rinsed with alcohol. Bipolar Ag/AgCl surface electrodes (diameter 14 mm, center-to-center distance 20 mm; Noraxon Dual Electrodes, Noraxon, Scottsdale, USA) were positioned and oriented bilaterally in accordance with the European Recommendations for Surface Electromyography.[35] Afterwards MVC tests were performed.

Movements of the Posturomed platform and the participants were captured by a 3-D motion capture system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK; 10 Vantage V8 and 6 Vero V2.2 cameras with a recording frequency of 200 Hz). Four reflective markers were fixed on the upper surface of the platform. Twenty reflective markers were attached to the participants' skin as shown in Figure 4.1.

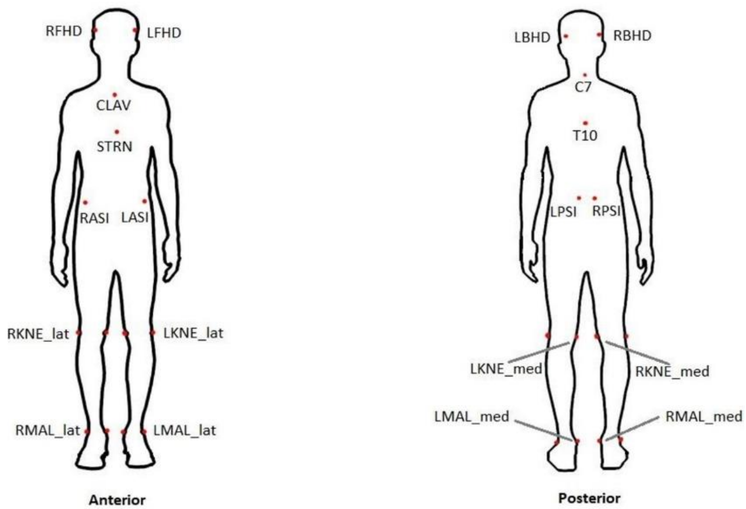

Figure 4.1: Reflective markers used for the five anatomical regions (ARs).

After training for the oral-motor task (except for the HAB group), balance task measurements began. Participants repeatedly stood on the platform, as described in the section "Balance tasks", and trials were recorded for 30 seconds. Between each trial, participants had 2 minutes of resting time to prevent fatigue. Measurements ended once the participants completed 12 valid trials, three for each direction.

4.3.2.4 Data analysis

In total, 576 trials (48 participants, three valid trials for each of the four directions) were analyzed. All data were recorded in Vicon Nexus 2.10 and exported for further processing in MATLAB R2020a (MathWorks; Natick, USA).

Marker data were filtered by use of a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz. Raw EMG data were filtered from 10 to 500 Hz by use of a fourth-order Butterworth band-pass filter, rectified and smoothed using a sliding average with a window frame of 30 ms and normalized to the MVC amplitudes (Hellmann et al., 2015).

To determine the respective mean EMG activities of the measured stomatognatic muscles before and after perturbation, two time windows were used. Before: from 2500 ms before the perturbation until the beginning of the perturbation; after: from the beginning of the perturbation to the third maximum amplitude (Figure 4.2), which corresponds to the DR window. The EMG activity of the measured stomatognatic muscles before and after perturbation for three trials for each direction and for each subject were averaged. Finally, R and L directions were re-sorted into ipsilateral (I) and contralateral (C) according to the standing leg of the participants.

Using the Posturomed marker data, DR (Eq. 4.1) (Kiss, 2011a) was calculated for each trial to evaluate the dynamic reactive balance performance. DR is a parameter that relates the actual damping to the critical damping value at which the system does not oscillate. It was calculated for the third amplitude (Figure 4.2) as suggested by Kiss et al. (2011a) In other words, DR in the present study quantified how well the platform was stabilized within the first three oscillations, with larger DR values representing stronger damping and thus better compensation of the perturbation.

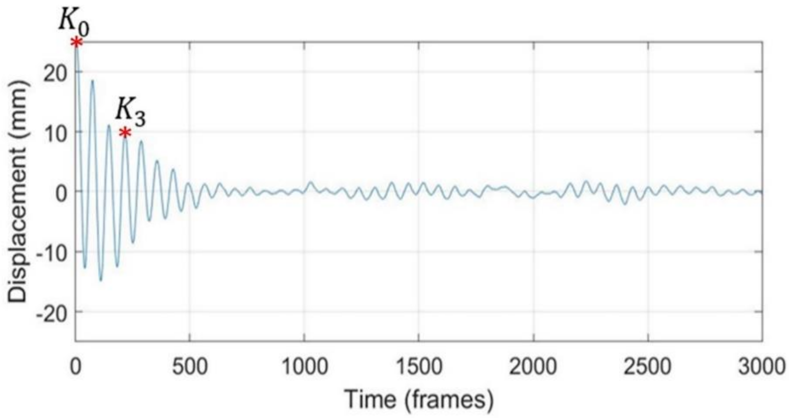

Figure 4.2: Damping ratio calculation. Initial maximum displacement (K0) and the third positive amplitude (K3) are shown.

In addition to DR as a measure of the performance, segmental kinematics were studied to analyze the underlying movement patterns. Similar to Ringhof et al. (Ringhof, Stein, et al., 2015), the body was divided into five anatomical regions (ARs; head, upper body, pelvis, knee and foot). For each AR, the centers were calculated using the markers shown in Figure 4.1 (head = RFHD, LFHD, RBHD, LBHD; upper body = CLAV, STRN, C7, T10; pelvis = RASI, LASI, RPSI, LPSI; knee = RKNE_med, RKNE_lat or LKNE_med, LKNE_lat; foot = RMAL_med, RMAL_lat or LMAL_med, LMAL_lat). The resulting path lengths in 3D were calculated for the time window defined by the DR. Since the size of this time window is trial-specific, each path length of an AR was divided by the corresponding time window for each subject and trial. This ultimately corresponds to the mean AR speed.

$$DR_i = \frac{\Lambda}{\sqrt{\Lambda_i^2 + 4\pi^2}} \quad ;\, where\ \ \Lambda_i = \frac{1}{3} ln \frac{K_0}{K_i} \ ,\ \ K_i : i^{th}\ positive\ amplitude \tag{4.1}$$

4.3.3 Statistics

IBM SPSS Statistics 25.0 (IBM Corporation, Armonk, NY, USA) was used to perform statistical tests. Performance parameters (DR) and kinematics parameters (mean AR speed) for three trials for each direction and for each subject were averaged. Kolmogorov-Smirnov and Mauchly's sphericity tests were conducted to confirm the normality and sphericity of data distribution, respectively. Greenhouse–Geisser estimates were used to correct for violations of sphericity.

Each of the four perturbation directions were analyzed separately for performance evaluation since postural response may differ depending on the perturbation direction (Akay & Murray, 2021; C. Chen et al., 2014; Freyler et al., 2015; Kiss, 2011b; Nonnekes et al., 2013). For each direction, a one-way ANOVA was performed to compare the groups' balance performances. For the segmental kinematics, a two-way ANOVA [5 ARs x 3 groups] was calculated if significant results were present at the performance level. Tukey *post-hoc* tests were performed in case of significant differences. The level of significance for all statistical tests was set *a priori* to $p < 0.05$. Partial eta squared (small effect: $\eta_p^2 < 0.06$; medium effect: $0.06 < \eta_p^2 < 0.14$; large effect: $\eta_p^2 > 0.14$) (Richardson, 2011) and Cohen's d (small effect: d < 0.50; medium effect: d = 0.5 – 0.8; large effect d > 0.8) (Cohen, 1992) were calculated as measures of effect size for ANOVA and *post-hoc* tests, respectively.

4.4 Results

4.4.1 Oral-motor task

All participants in each group fulfilled their individual oral-motor task, in the sense that it was performed before the perturbation and during their balance recovery.

- **JAW:** mean EMG activity of the musculus masseter was 5.59 ± 3.72% MVC before perturbation and 4.89 ± 3.04% MVC after perturbation.
- **TON:** all participants showed a mean EMG activity of 3.96 ± 2.35% MVC of the FoMM before the perturbation, and of 3.44 ± 2.06% MVC after perturbation.
- **HAB:** 3 of the 16 participants showed consistent habitual clenching mean EMG activity of the musculus masseter of 6.12 ± 3.30% MVC before perturbation and 6.39 ± 2.64% MVC after perturbation. The remaining 13 participants consistently showed a constant resting EMG activity of the musculus masseter of 0.31 ± 0.22% MVC before perturbation and 0.34 ± 0.29% MVC after perturbation.

4.4.2 Dynamic balance performance

The mean time window of DR was 1.13 ± 0.01 s. The ANOVA results revealed that groups had significantly different performances in direction F (forwards acceleration of the platform after release) with a high effect size ($p < 0.001$, $\eta_p^2 = 0.349$). According to the *post-*

hoc test results, the JAW group had a significantly higher DR compared to both HAB ($p = 0.001$, $d = 1.03$) and TON ($p < 0.001$, $d = 1.40$) groups with high effect sizes.

There were no significant differences in the remaining directions (B: $p = 0.226$, η_p^2= 0.064; I: $p = 0.920$, η_p^2= 0.004; C: $p = 0.607$, η_p^2= 0.022). The statistical results as well as the mean and the standard deviation of DRs for each group and each direction are shown in Table 4.1.

Table 4.1: Damping ratio (DR) for all groups and directions and the corresponding ANOVA results.

DR	Jaw clenching (JAW)	Tongue pressing (TON)	Habitual (HAB)	p	η_p^2
B	0.062 ± 0.003	0.055 ± 0.003	0.055 ± 0.003	0.226	0.064
F	0.066 ± 0.003	0.046 ± 0.003	0.049 ± 0.003	**< 0.001**	**0.349**
I	0.045 ± 0.003	0.046 ± 0.008	0.048 ± 0.005	0.920	0.004
C	0.043 ± 0.005	0.040 ± 0.004	0.037 ± 0.004	0.607	0.022

DRs are given as mean ± standard deviation. B = back, F = forward, I = ipsilateral, C = contralateral.

4.4.3 Segmental kinematics

Segmental kinematics were analyzed for direction F because it was the only direction that showed a significant difference between groups. The results of two-way ANOVA [5 ARs x 3 groups] revealed a significant group effect with a medium effect size ($p < 0.001$, η_p^2= 0.09) and a significant AR effect with a high effect size ($p < 0.001$, η_p^2= 0.83). However, there was no interaction effect between groups and ARs ($p = 0.550$, η_p^2= 0.03). An overview of the mean AR speed data is illustrated in Figuree 4.3.

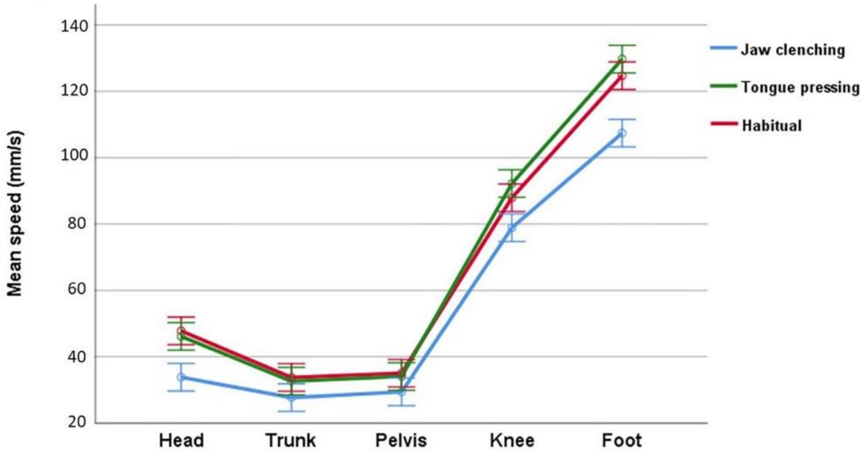

Figure 4.3: Mean speed of anatomical regions (ARs) for all groups. Error bars show ± SD.

The *post-hoc* test results for the group effect showed that the JAW group had significantly lower speeds compared to both HAB ($p < 0.001$, $d = 2.80$) and TON ($p < 0.001$, $d = 2.97$) groups with high effect sizes. The *post-hoc* test for the AR effect showed that the foot had the highest mean speed, and that it was significantly higher than the other regions with high effect sizes (knee: $p < 0.001$, $d = 1.59$; pelvis: $p < 0.001$, $d = 4.57$; trunk: $p < 0.001$, $d = 4.63$; head: $p < 0.001$, $d = 3.43$). The knee had the second highest mean speed, and this was significantly higher than the pelvis ($p < 0.001$, $d = 3.99$), trunk ($p < 0.001$, $d = 4.04$) and head ($p < 0.001$, $d = 2.39$), each with a high effect size. The mean speeds of the trunk and pelvis did not differ significantly from each other and were the lowest among all ARs. The head had a significantly higher mean speed than the pelvis ($p = 0.036$, $d = 0.69$) and trunk ($p = 0.009$, $d = 0.74$) with medium effect sizes.

4.5 Discussion

The aim of this study was to investigate the effects of motor activity of the masticatory system in the form of jaw clenching (JAW) and tongue pressing (TON) on dynamic reactive balance performance, and to subsequently explain significant performance effects on the level of segmental kinematics. This study showed that JAW enhanced the dynamic reactive balance performance significantly in the forward direction of perturbation, demonstrated by an increased DR that was accompanied by a decreased mean speed of the analyzed ARs. In the remaining three directions, no significant changes occurred. Based on these findings, two conclusions can be drawn: (1) JAW can improve dynamic reactive balance but the occurrence of the positive effects seems to be task-specific and not general. (2) TON seems not to have any observable effects on dynamic reactive balance performance, at least when evaluated on an oscillating platform.

4.5.1 Jaw clenching improves dynamic reactive balance in a task-specific way

Dynamic reactive balance was assessed by use of an oscillating platform which was randomly perturbed in four different directions. The four directions of perturbation were analyzed independently, as suggested by Freyler et al. (2015) because muscle spindles provide different information dependent on the direction as well the velocity of perturbations (Akay & Murray, 2021). In addition, the direction of surface translation is an important factor for the sensation, processing and output of the postural responses (Freyler et al., 2015; Nonnekes et al., 2013). Therefore, the four directions of perturbations were treated as different tasks.

The participants' task was to compensate the perturbations as quickly as possible. To be able to assess the quality of the task solution, the DR was chosen because it is a proper method to characterize reactive balancing capacity after sudden perturbations (Kiss, 2011a). The results for the DR parameter revealed that jaw clenching improved the dynamic reactive balance performance only in the F direction. This finding is in line with the perturbation direction dependency of postural control (Akay & Murray, 2021; C. Chen et al., 2014; Freyler et al., 2015; Kiss, 2011b; Nonnekes et al., 2013). Explicitly, F indicates that the platform was accelerated forwards after release, which led to posterior acceleration of the body with respect to the support surface. A study analyzing the effects of the type and direction of support surface perturbation on postural responses (C. Chen et al., 2014) showed that a forward translation is more unstable than a backward one and led to faster muscle activation as well as to faster and larger hip and knee joint movements. In another study comparing postural responses to backward and forward perturbations (Nonnekes et al., 2013), it was shown that a startling auditory stimulus resulted in better postural control but only in the backward body sway condition. Therefore, the authors suggested that postural responses to backward and forward perturbations may be processed by different neural circuits. In line with these findings, dynamic reactive balance performance improvement in direction F may be attributed to a higher difficulty level of the task compared to direction B. It may also be a reasonable explanation that JAW is associated with adaptations in neural circuits that are recruited during forward translation of the platform.

Segmental kinematics were analyzed in direction F, aiming at understanding the underlying postural control strategies that improved dynamic reactive balance. The two main findings were: (1) across the three groups the foot had the highest mean speed, followed by the knee and head. The mean speeds of the trunk and pelvis did not differ from each other and were lower than the mean speeds of the foot, knee and head; (2) the JAW group had a lower mean AR speed compared to both the HAB and TON groups. Consequently, the different oral-motor tasks did not affect the relationship between regional mean speeds (see also Figure 4.3).

The finding that the trunk and pelvis had the lowest mean speed across ARs may be explained by the stability prioritization of proximal segments over distal ones during balancing (Hughey & Fung, 2005; Munoz-Martel et al., 2019). The speeds of lower body ARs were higher than the head, possibly because platform perturbations are compensated mainly at the knee and ankle joints and the head remains stiller compared to lower body regions. In addition, the participants were instructed to fix their gaze at a stationary target, which possibly also contributed to the lower speed of the head. The second main finding, that the JAW group had an overall lower speed in ARs than the HAB and TON groups, may be attributed to enhanced body stiffness, similar to the study by Ringhof, Stein, et al. (2015) However, merely based on mean AR speed results, it is difficult to draw this conclusion. Therefore, in future studies the activity of trunk muscle groups should be analyzed.

4.5.2 Influence of stomatognatic motor behavior on dynamic reactive balance performance

There is no consensus in existing literature about the effects of jaw clenching on motor behavior. It can possibly be explained by the stimulation of periodontal receptors or by the different proprioceptive inputs due to different jaw relations. Another explanation could be the facilitation of human motor system excitability. In the present study, we hypothesized that both JAW and TON would influence dynamic reactive balance performance. This could be due to either neurophysiological coupling or an effect shown in posture-cognition studies, showing that the release of attention away from balance control and towards a secondary task - in this case, to clench or press the tongue against the palate - can enhance postural stability (Fraizer & Mitra, 2008). In the latter case, both JAW and TON would enhance postural stability. Since there is no significant difference between TON and HAB in the present study, it was concluded that dynamic reactive balance performance improvement was not associated only with the stomatognatic motor activity in general or with the dual-task paradigm. Contrarily, the significant differences between the JAW and the HAB/TON groups indicate a specific effect of instructed jaw clenching activity but in a task specific manner. It should also be noted that both the partial eta squared (η_p^2= 0.349) and Cohen's d ($d_{JAW-HAB}$ = 1.03 and $d_{JAW-TON}$ = 1.40) results indicated high effect sizes for group comparisons which strengthen the explanatory power of the results considerably and minimize the possibility that the findings were random effects.

A secondary finding of this study is that participants in the HAB group showed different oral-motor behaviors. While in 13 participants the mandible was in a resting position with no relevant muscle activity of the jaw closing muscles, three participants showed clenching activity in the sense of muscle activity comparable to the JAW group. The percentage distribution of these different habitual motor behaviors is consistent with available data regarding the prevalence of awake bruxism (Manfredini et al., 2013). Since the clenching activity was performed before the perturbation and during the balance recovery, in these individuals clenching might also be part of the physiological repertoire during coping with demanding motor tasks (Ringhof et al., 2016). However, further studies are needed to clarify this hypothesis.

Another interesting finding was regarding the segmental kinematics. Mean AR speeds of these three participants in the HAB group with clenching were larger than the mean AR speeds of the HAB group without clenching as well as than those of the TON group and the JAW group (See Appendix S1 Table1). This might indicate that conscious, non-habituated clenching has a different influence on balance behavior in comparison to participants who perform clenching as a part of their physiological repertoire. However, this hypothesis is vague and needs to be investigated in further studies.

4.5.3 Limitations

All the participants were physically active adults. Accordingly, statements can only be made for this age group. Deliberate care was taken to ensure a homogeneous sample to minimize altered postural control mechanisms due to, for example, age (M. Henry & Baudry, 2019) or neurological disorders (Delafontaine et al., 2020). The participants were allocated into three groups with different oral-motor tasks. On the one hand, this can be considered as a limitation because of the possible baseline performance differences between groups. However, in order to overcome this problem, a baseline measurement was conducted in habitual biting condition to parallelize the three different groups in terms of both performance and gender. The statistical results revealed no baseline performance differences between the three groups (p = 0.767). One might think that it would have been purposeful if all subjects had performed all oral-motor tasks. However, "habitual" in this study meant that no instruction was given regarding the status of the masticatory organ.

Thus, an unconscious, ancestral behavioral pattern of the masticatory system during the balancing task could be expected. By definition, an "instructed" behavioral pattern can never correspond to an unconsciously performed behavior. An instructed “habitual” oral-motor behavior would have potentially resulted in dual-task effects and therefore, it would have been ultimately difficult to distinguish between cognitive and postural effects (i.e. thinking about the instructed behavior and performing different oral-motor tasks, respectively). On the other hand, building of three groups provided two main advantages. Firstly, possible carry over effects between different oral-motor tasks were avoided. For example, some physiological effects could have still existed after jaw clenching or tongue pressing such as an increased excitability of the human motor system or muscles of the masticatory system in a fatigued state. Secondly, if all the participants conducted all of the three oral-motor tasks for each of the four directions separately, the valid trials needed would be 36. Considering the invalid trials as well, the total trials conducted could increase to a level at which fatigue set in and data quality decrease consequently.

In this study, the Posturomed oscillating platform was chosen to assess dynamic reactive balance performance. The Posturomed is a widely-used device for scientific studies as well as for training or rehabilitation (Freyler et al., 2015; Kiss, 2011a; Munoz-Martel et al., 2019; Petró et al., 2018). However, it should be noted that stabilizing a moving platform represents a different balance task than balancing the body on a rigid surface (Alizadehsaravi et al., 2020). Therefore, it is worth adding that the results in this study cannot directly be transferred to stable ground conditions (e.g., recovering from a perturbation during upright standing on a rigid surface), since balance performance under various dynamic balance conditions cannot be considered directly interchangeable (Ringhof & Stein, 2018).

The dynamic balance performance was assessed by use of DR as suggested in other studies (Kiss, 2011a; Petró et al., 2018). Mean speed of ARs was chosen for kinematic analysis following Ringhof, Stein, et al. (2015) as explained in detail in the “Data analysis” section. Despite being widely used parameters, it is important to note that the calculation of these parameters is based on linear methods, and such traditional approaches for assessing postural stability may not fully characterize the non-linear properties of postural control (Cavanaugh et al., 2005). Therefore, it would be advisable to perform non-linear analysis using, for example, maximum-Lyopunov exponent (Munoz-Martel et al., 2019) or entropy measures (Cavanaugh et al., 2005) to further extend the knowledge regarding the effects of oral-motor activity on postural control.

4.6 Conclusion and Outlook

The aim of this study was to investigate the influence of different functional stomatognatic statuses (i.e. JAW, TON, HAB) on postural performance during a dynamic reactive balance task. To the best of our knowledge, this study was the first to analyze the effects of JAW on dynamic reactive balance performance and also the first to investigate the effects of TON related to postural control. The results showed that JAW improves dynamic reactive balance but the occurrence of the positive effects seems to be task-specific and not general. Improved dynamic balance performance of the JAW group was associated with overall decreased speeds of ARs, but without any AR-specific changes due to functional stomatognatic status. In addition, TON seems not to have any observable effects on dynamic balance performance, at least when evaluating it with an oscillating platform. The results show that dynamic reactive balance performance improvement in this study was not associated with stomatognatic motor activity per se or the with dual-task paradigm, but in particular with jaw clenching activity.

Therefore, the direction-dependent improvement in dynamic reactive balance performance due to JAW should be investigated in more detail. For this purpose, future studies should analyze control strategies at the muscular level, such as muscular co-contractions, to reveal if postural control in the presence of controlled oral-motor activities leads to stiffer joints in a directionally dependent manner in the Posturomed task. Subsequently, an in-depth analysis of adaptations in motor coordination on a kinematic as well as on a muscular level would be useful, for example by use of matrix factorization algorithms to extract kinematic (Federolf, 2016) or muscle synergies (Munoz-Martel et al., 2019).

Considering the initially stated potential clinical relevance of this study in terms of an influence of oral-motor training on the risk of falls, it is too early to draw final conclusions. However, previous studies have found jaw clenching can stabilize body sway in the anterior-posterior direction under static conditions (Hellmann et al., 2015; Ringhof, Stein, et al., 2015), similar to results from the present study under dynamic conditions. This might therefore be an aspect which should be further investigated, since it might be a valuable strategy which could reduce the risk of falls in general or maybe especially in elderly people.

5 Study II – Modulation of Reflex Activities – Dynamic Reactive Balance

Accepted version of the paper published as

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5.1 Abstract

Background: Jaw clenching improves dynamic reactive balance on an oscillating platform during forward acceleration and is associated with decreased mean sway speed of different body regions.

Objective: It is suggested that jaw clenching as a concurrent muscle activity facilitates human motor excitability, increasing the neural drive to distal muscles. The underlying mechanism behind this phenomenon was studied based on leg and trunk muscle activity (iEMG) and co-contraction ratio (CCR).

Methods: Forty-eight physically active and healthy adults were assigned to three groups, performing three oral-motor tasks (jaw clenching, tongue pressing against the palate, or habitual lower jaw position) during a dynamic one-legged stance reactive balance task on an oscillating platform. The iEMG and CCR of posture-relevant muscles and muscle pairs were analyzed during platform forward acceleration.

Results: Tongue pressing caused an adjustment of co-contraction patterns of distal muscle groups based on changes in biomechanical coupling between the head and trunk during static balancing at the beginning of the experiment. Neither iEMG nor CCR measurement helped detect a general neuromuscular effect of jaw clenching on the dynamic reactive balance.

Conclusion: The findings might indicate the existence of robust fixed patterns of rapid postural responses during the important initial phases of balance recovery.

5.2 Introduction

Postural control is a special form of motor control, an indispensable prerequisite for human movement (Horak & Earhart, 2021). Impaired postural control is a major risk factor for falls, and training has a central role in preventing them (Rubenstein, 2006). Multiple sensory signals from the visual, vestibular, and somatosensory systems are used to correct instability in balance control (Takakusaki, 2017). However, the influence of oral-motor activities was also discussed because extensive research showed neuromuscular effects of oral-motor activity (e.g., jaw clenching and tongue pressing) on upright posture stabilization. Evidence indicates that jaw clenching has a reproducible stabilizing effect on human body-sway in hip width stance (Hellmann et al. 2011a) and improves postural control during bipedal narrow and single-leg stance [reduced center of pressure (COP) displacement and trunk and head oscillations] (Ringhof, Stein, et al., 2015) based on increased neuromuscular co-contraction pattern precision (Hellmann et al., 2015). Since balance control is task-specific rather than a general ability, it is useful to study balance tasks other than static stance (Ringhof & Stein, 2018). Studies showed the stabilizing effects of oral-motor tasks when standing on firm and foam surfaces (Alghadir et al., 2015c; Bracco et al., 2004; Julià-Sánchez et al., 2020; Kushiro & Goto, 2011; Ringhof, Leibold, et al., 2015; Sakaguchi et al., 2007; Sforza et al., 2006; Tomita et al., 2021) and during dynamic balancing tasks on unstable platforms (Fadillioglu et al., 2022a). Fadillioglu et al. (2022a) compared the effect of jaw clenching, tongue pressing against the palate, and habitual lower jaw position on postural performance during a dynamic reactive balance task on an oscillating platform. Using the Lehr's damping ratio of the first three maximum amplitudes after the perturbation (Kiss, 2011a) and the mean sway speed of selected anatomical regions (head, trunk, pelvis, knee, and foot), they showed that jaw clenching improved the dynamic reactive balance during forward acceleration of the platform (i.e. an imminent fall backward). However, jaw clenching showed no stabilizing effects during simulated falls forward (Fadillioglu et al., 2022a; Ringhof et al., 2016).

As an explanation for the influence of jaw clenching on balancing behavior, it was suggested that concurrent muscle activities contributed to the facilitation of human motor excitability and increased the neural drive to distal muscles (Ebben, 2006; Ebben et al., 2008). It was hypothesized that the jaw clenching effect on posture was induced by somatosensory input modulation and facilitation of muscles such as the ankle extensor and flexor muscles (Miyahara et al., 1996; Takada et al., 2000) and concomitant attenuation of reciprocal Ia inhibition (Takada et al., 2000). Neuroanatomical connections and projections of the trigeminal nerve to structures associated with postural control form the basis for these effects (Buisseret-Delmas et al., 1999; Devoize et al., 2010; Ruggiero et al., 1981).

Current evidence indicates: First, jaw clenching improves performance during dynamic reactive balance tasks under certain conditions. Second, jaw clenching influences the excitability of the motor system and thus enhances reflex responses and neurophysiological effects, detectable based on muscle activity and/or co-contraction patterns. Therefore, this study analyzed the reflex activities of various postural muscles in relevant reflex phases using a dataset —first published in 2022 in this journal (Fadillioglu et al., 2022a)— in which we found improved dynamic reactive balance during forward platform acceleration under the influence of jaw clenching. We hypothesized that muscle activity and co-contraction pattern (CCR) of relevant muscle pairs in reflexive phases would change under the influence of jaw clenching and tongue pressing.

5.3 Methods

5.3.1 Participants

Forty-eight physically active adults (23 male, 25 female; age: 23.8 ± 2.5 years; height: 1.73 ± 0.09 m; body mass: 69.2 ± 11.4 kg) participated in this study. The dominant leg of each participant was determined by self-reports or, in case of uncertainties, by test trials on the oscillating platform (Ringhof & Stein, 2018). All participants gave their written informed consent before the start of the experiments. The participants confirmed they were naïve to the balancing task, had no neurological or muscular diseases, and were physically active (regular sporting activity, at least thrice weekly). Moreover, the participants showed no symptoms or signs of temporomandibular disorders assessed by the research diagnostic criteria for temporomandibular disorders (RDC/TMD (Dworkin & LeResche, 1992)) and had full dentition, except for 3rd molars, in neutral occlusion. The study was approved by the Ethics Committee of the Karlsruhe Institute of Technology.

5.3.2 Experimental procedure

5.3.2.1 Balance tasks

Dynamic reactive balance was evaluated using the Posturomed oscillating platform (Haider-Bioswing, Weiden, Germany). This commercial device consists of a rigid platform (60 x 60 cm, 12 kg) and eight 15-cm steel springs of identical strength and can swing in all directions along the horizontal plane. The Posturomed was previously used to systematically investigate dynamic reactive balance performance after platform displacements (Freyler et al., 2016; Keller et al., 2012; Pfusterschmied, Stöggl, et al., 2013). An automatic custom-made release system was used to accelerate the platform horizontally (up to 2.5 cm) in one of four possible directions: back, front, left, and right (Fadillioglu et al., 2022a). These indicate the direction to which the platform was accelerated after release (e.g., front indicates that the platform was accelerated forward after release, leading to posterior body sway relative to the platform).

The perturbation direction was presented in a randomized order, and the participants' task was to compensate for the perturbation as quickly as possible. Before each trial, the participants were asked to stand with the dominant leg in the center of the Posturomed, the non-dominant leg in the air, hands on hips, and look straight ahead at an eye-level marker 4 m away (Figure 5.1). If a participant lost balance, touched the ground with the non-dominant foot, released one of the hands from the hip, changed the dominant foot position, or did not perform the oral-motor activity properly, the trial was considered invalid and was repeated.

5.3.2.2 Group assignment and oral-motor tasks

The participants were allowed to familiarize themselves with the Posturomed at the beginning of the trial. This familiarization included two static trials and two trials with perturbation in the back direction. Subsequently, baseline measurements were performed, also in the back direction, to group the participants based on their dynamic reactive balance performance, quantified by Lehr's damping ratio (Fadillioglu et al., 2022a; Kiss, 2011a). Statistical tests found no baseline performance differences between the three groups (ANOVA, $p = 0.767$). Attention was also given to ensuring equal sex distribution within the groups. Each group had to perform one of the following oral-motor tasks while balancing on the platform during each trial:

- **JAW:** instructed; controlled submaximal jaw clenching during occlusal loading
- **TON:** instructed; controlled submaximal tongue pressing against the palate; stomatognathic muscle activity without occlusal loading
- **HAB:** without instruction; habitual stomatognathic behavior

Figure 5.1: A participant is standing with the dominant leg in the center of the Posturomed, the non-dominant leg in the air, hands on the hips, and looking straight ahead.

Oral-motor activity based on group assignment was measured by electromyography (EMG; detailed information in the subsection “Data collection”). Before the measurements, the JAW group was trained to achieve submaximal clenching at a force of 75 N using a RehaBite (Plastyle GmbH, Uttenreuth, Germany), a medical training device consisting of liquid-filled plastic pads and working based on hydrostatic principles. Muscle activity was displayed during training using the EMG system. The training was terminated once the participant successfully applied a stable force of 75 N (which resulted in a mean EMG activity of about 5% of their maximum voluntary contraction, MVC). For the training, the TON group applied a submaximal force with the tip of the tongue against the anterior hard palate. The training was terminated once the participants achieved a consistent EMG activity at 5% of their MVC, measured in the region of the m. digastricus venter anterior. The training for both groups lasted approximately five minutes. The corresponding EMG levels of jaw clenching and tongue pressing activities were used during the measurements to determine whether the submaximal jaw clenching or tongue pressing force was reached. The JAW group performed their submaximal jaw clenching task on an Aqualizer intraoral splint (Medium volume; Dentrade International, Cologne, Germany) during the balance task measurement. The HAB group received no training or instructions regarding oral-motor activity.

5.3.2.3 Data collection

A wireless EMG system (Noraxon, Scottsdale, USA) operating at 2,000 Hz was used to measure EMG activity. EMG activity was derived from the M. masseter (Mass) for the JAW and HAB groups and the suprahyoid muscles at the base of the mouth for the TON group, measured near the digastricus venter anterior muscle. The EMG signal was also derived from the following postural task-related skeletal muscles: M. gastrocnemius medialis (GM), M. soleus (SOL), M. tibialis anterior (TA), M. peroneus longus (PL), M. tensor fascia latae (FL), M. semitendinosus (SEM), M. biceps femoris (BF), M. rectus femoris (RF), M. vastus medialis (VM), Mm. obliquus externus (OBL), Mm. rectus abdominis (ABS), and Mm. erector spinae iliocostalis (ES) (Figure 5.2).

5.3.2.4 Data analysis

Since significant effects of JAW in dynamic reactive balancing performance were only found for perturbation in the forward direction (Fadillioglu et al., 2022a), only the dataset of this direction was used for further analysis.

EMG data were filtered using a fourth-order Butterworth band-pass filter (10-500 Hz) and then rectified and normalized to the MVC amplitudes. For reflex activity analysis, four phases were considered and defined based on the perturbation onset: (1) PRE: the time window just before the perturbation onset (–100 to 0 ms); (2) SLR: short latency response (30 to 60 ms); (3) MLR: medium latency response (60 to 85 ms); (4) LLR: long latency response (85 to 120 ms). These phases were defined following previous studies (Freyler et al., 2015; Taube et al., 2006). The integrated EMG (iEMG) was calculated for each muscle and reflex phase. Furthermore, the following muscle pairs were selected for co-contraction analysis: GM-TA, SOL-TA, TA-BF, VM-BF, RF-BF, GM-RF, PL-SOL, VM-SEM, ABS-ES, SEM-FL, and OBL-ES. The dominant (d) and non-dominant (nd) sides were calculated separately for ABS-ES and OBL-ES. The co-contraction ratio (CCR) was calculated as lower/higher EMG for each time point i, and the average CCR was calculated for each phase (Hellmann et al., 2015).

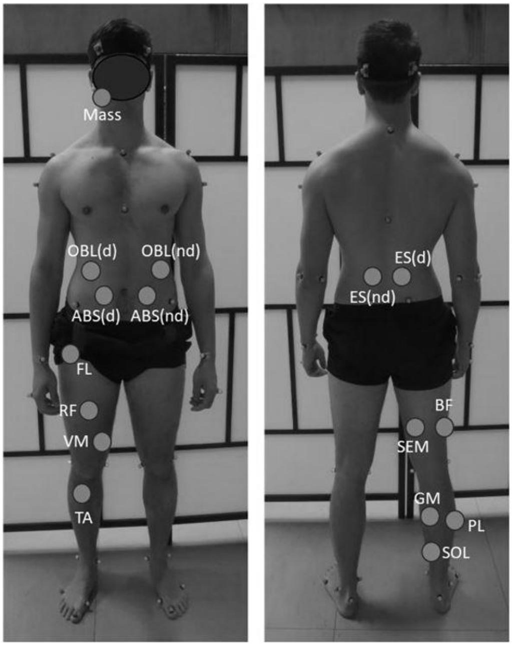

Figure 5.2: The EMG signal was derived from the M. masseter (= Mass) and postural task-related skeletal muscles: OBL = Mm. obliquus externus, ABS = Mm. rectus abdominis, FL = M. tensor fascia latae, RF = M. rectus femoris, VM = M. vastus medialis, TA = M. tibialis anterior, ES = Mm. erector spinae iliocostalis, BF = M. biceps femoris, SEM = M. semitendinosus, GM = M. gastrocnemius medialis, PL = M. peroneus longus, SOL = M. soleus. d = dominant. nd = non-dominant

5.3.2.5 Statistical analysis

Statistical tests were performed in IBM SPSS Statistics for Windows, Version 29.0 (IBM Corporation, Armonk, NY, USA). The average values over three trials were calculated for dependent parameters (i.e. iEMG and CCR). The normality of the data distributions was tested by Kolmogorov-Smirnov tests. A one-way ANOVA or a Kruskal-Wallis test was performed for each phase (PRE, SLR, MLR, and LLR) and each dependent parameter, with the group (INT, JAW, and HAB) as an independent parameter. The significance level was set *a priori* to $p < 0.05$. Partial eta-squared was used to quantify the effect sizes (small effect: $\eta_p^2 < 0.06$; medium effect: $0.06 < \eta_p^2 < 0.14$; large effect: $\eta_p^2 > 0.14$) (Cohen, 1988). In case of significant differences, pairwise post-hoc tests were conducted.

5.4 Results

5.4.1 Oral-motor task

The participant performed the oral-motor tasks during all four phases (Table 5.1a). The EMG activities of M. masseter in JAW and the suprahyoidal muscles in TON were significantly higher than in HAB (Table 5.1b, c) in all phases. Therefore, the instructed oral-motor tasks were fulfilled.

Table 5.1a: iEMG of M. masseter and the suprahyoid muscles in MVC % at four critical phases

Muscle	Group		PRE	SLR	MLR	LLR
M. masseter	JAW	Mean	4.94	4.75	4.92	4.91
		SD	3.01	2.99	3.12	2.86
	HAB	Mean	1.36	1.20	1.11	1.38
		SD	3.04	2.62	2.32	2.97
Suprahyoidal muscles	TON	Mean	3.35	3.52	3.19	3.34
		SD	2.32	2.57	2.05	2.20

Table 5.1b: Comparison of iEMG of M. masseter and the suprahyoid muscles at four critical phases between the three groups using the Kruskal-Wallis test.

PRE		SLR		MLR		LLR	
p	η_p^2	p	η_p^2	p	η_p^2	p	η_p^2
< 0.001	0.225	**< 0.001**	0.237	**< 0.001**	0.286	**< 0.001**	0.234

5.4.2 iEMG activity of the postural muscles

No significant differences were found between the JAW, TON, and HAB groups in the iEMG activity of the investigated postural muscles during any of the four phases studied (PRE, SLR, MLR, and LLR; Appendix S2 Table1).

5.4.3 Co-contraction ratio (CCR)

Before perturbation (PRE), VM-SEM and OBL-ES(d) in the TON group showed significantly lower CCR values than in the HAB group. In the SLR and MLR phases, OBL-ES(d) in the TON group showed significantly lower CCR values than in the JAW group and for MLR, also than in the HAB group.

In LLR, PL-SOL showed significantly higher CCR values in the JAW and TON groups than in the HAB group. The relevant data on significant results are listed in Tables 5.2a-c. The full data of CCR values can be viewed in Appendix S2 Table2.

Table 5.1c: Post-hoc results for cases with significant effects in the Kruskal-Wallis test for iEMG analysis.

Phase	Groups		p
PRE	JAW	HAB	**<0.001**
	HAB	TON	**0.001**
	TON	JAW	0.240
SLR	JAW	HAB	**<0.001**
	HAB	TON	**<0.001**
	TON	JAW	0.384
MLR	JAW	HAB	**0.002**
	HAB	TON	**<0.001**
	TON	JAW	0.193
LLR	JAW	HAB	**<0.001**
	HAB	TON	**0.002**
	TON	JAW	0.245

5.5 Discussion

This study aimed to elucidate the neuromuscular mechanism behind the measured jaw-clenching effects on dynamic reactive balance after forward platform acceleration (i.e. an imminent fall backward). For this purpose, activities and co-contraction patterns of posture-relevant muscles and muscle pairs were analyzed before and during relevant reflex phases after perturbation. Previously published data revealed that jaw clenching led to a better dynamic reactive balance during forward platform acceleration than habitual stomatognathic behavior and tongue pressing (Fadillioglu et al., 2022a).

Table 5.2a: Co-contraction ratio (CCR) of selected muscle pairs at four critical phases.

Muscle pair	Group		PRE	SLR	MLR	LLR
PL-SOL	JAW	Mean	0.34	0.34	0.33	0.35
		SD	0.04	0.05	0.07	0.05
	HAB	Mean	0.33	0.35	0.34	0.30
		SD	0.04	0.06	0.07	0.06
	TON	Mean	0.34	0.33	0.34	0.35
		SD	0.05	0.06	0.06	0.05
VM-SEM	JAW	Mean	0.32	0.31	0.29	0.33
		SD	0.05	0.06	0.08	0.07
	HAB	Mean	0.33	0.29	0.32	0.32
		SD	0.06	0.06	0.07	0.07
	TON	Mean	0.27	0.28	0.28	0.27
		SD	0.08	0.09	0.10	0.08
OBL-ES (d)	JAW	Mean	0.36	0.38	0.37	0.36
		SD	0.06	0.07	0.07	0.06
	HAB	Mean	0.39	0.37	0.37	0.38
		SD	0.06	0.07	0.07	0.07
	TON	Mean	0.32	0.31	0.30	0.32
		SD	0.09	0.08	0.09	0.09

Table 5.2b: One-way ANOVA results for the co-contraction ratio (CCR) at four critical phases in direction F.

	PRE		SLR		MLR		LLR	
	p	η_p^2	p	η_p^2	p	η_p^2	p	η_p^2
PL-SOL	0.714	0.015	0.736	0.014	0.816	0.009	**0.010**	0.185
VM-SEM	**0.037**	0.136	0.566	0.025	0.484	0.032	0.082	0.105
OBL-ES (d)	**0.026**	0.150	**0.018**	0.164	**0.009**	0.188	0.080	0.106

Significant results are indicated in bold.

5.5.1 Oral-motor task

The EMG activity of M. masseter and the suprahyoid muscles in the JAW and TON groups was significantly higher than in the HAB group, indicating that the oral-motor tasks were fulfilled during all experimental phases.

5.5.2 Postural muscle reflexes

No differences were found between the groups at any reflex phase of the anticipatory and compensatory postural responses (i.e. neither before nor after perturbation). Therefore, at the iEMG level, the active groups (JAW and TON) showed no effect. Consequently, no general effect of oral-motor activities on muscular activity in the lower trunk and legs was evident, in agreement with the findings of Hellmann et al. (2011a) under static conditions. We also found no significant changes in the iEMG activity of the leg muscles under the influence of oral-motor activity. Our findings might seem somewhat unexpected, considering that earlier research emphasized that reflex responses were facilitated by voluntary jaw clenching (Miyahara et al., 1996; Takada et al., 2000). Noteworthy, those effects were observed in participants comfortably seated, with the knee and foot joint angles at 120° and 100°, respectively. In our study, participants stood on one leg, with the ankle in a neutral position and the knee and hip joints almost fully extended. This increased postural demand (as in the transition from lying to standing or bipedal to unipedal standing) has been shown to be accompanied by modulation of soleus and tibialis H-reflex amplitudes (Kim et al., 2013; Unger et al., 2019; Zehr, 2002). More precisely, increases in postural demand were correlated with decreases in reflex amplitudes. The proposed mechanism behind this presynaptic inhibition is a shift in the central nervous system to increase voluntary balance control (Y. Chen & Zhou, 2011; Huang et al., 2009). However, whether jaw clenching could counteract this presynaptic inhibition in standing positions has not been investigated.

5.5.3 CCR of postural muscles in the various reflex phases

The balance task used in this experiment involved challenging the response to platform displacement relative to the participant. Since the platform can oscillate, movements in all directions in the transverse plane were possible. The forward platform acceleration in the considered time window (100 ms pre-perturbation to 120 ms post-perturbation) resulted in an anterior platform displacement. Ground displacement in an anterior-posterior direction is mostly compensated by increasing ankle and knee joint deflections in the sagittal plane and range of motion of these joints could help lower the center of gravity, leading to a fast reacquisition of a stable one (Freyler et al., 2015). Therefore, the increased balance recovery performance found after perturbation could be achieved through changes in the neuromuscular mechanisms that control the distal strategy mentioned above (Freyler et al., 2015).

5.5.4 Anticipatory postural adjustments

Studies found that tongue pressing (Alghadir et al., 2015a), jaw clenching, and chewing (Hellmann et al., 2011a) had stabilizing effects on COP displacements during quiet stance under static conditions. Similarly, the influence of jaw clenching on the co-contraction pattern of the leg muscles under such conditions has been reported (Hellmann et al., 2015). Based on these findings, an influence of both oral-motor tasks on the CCR could be expected under the steady-state condition of the balance task in the PRE experimental phase, particularly for the JAW group. However, tongue pressing against the palate, but not jaw clenching, resulted in a lower CCR than the habitual stomatognathic status. Therefore, it is unlikely that the tongue-pressing effect was based on modulating the somatosensory input and/or reflex facilitation. From a biomechanical standpoint, another hypothesis arises: a pronounced activity of the jaw-closing muscles requires no additional cervical muscle activity to stabilize the position or relation between the lower and upper jaws and the rest of the body. However, pressing the tongue against the palate requires hyoid bone stabilization by increased activity of the supra- and infrahyoidal muscles and might, therefore, influence the coordination between the head and trunk during the balancing task. Consequently, measurable adjustments in the intermuscular co-contraction pattern might be needed to coordinate the spatial alignment between the body segments by altering the positions of the hip and knee joints. This could proportionally explain the measurable influence of tongue pressing on the CCR of the lower trunk and thigh muscles during steady-state balancing in the PRE phase.

5.5.5 Compensatory postural adjustments

The neuromuscular compensation for the platform acceleration is realized by various subsystems and neuronal structures involved in compensatory postural responses. Postural responses became more voluntarily controlled with time after the perturbation onset, while muscle activity was modulated by the mono- and polysynaptic pathways during the SLR and MLR phases, respectively (Taube et al., 2006). Determined by the anatomical properties and function, the shank muscles — which are “near” the postural disturbance — serve as prime movers to give a direct corrective response by varying the ankle joint position (Freyler et al., 2015; Moore et al., 1988). During the SLR phase, this muscle activity is modulated by monosynaptic reflexes (Taube et al., 2006). Although jaw clenching could facilitate peripheral monosynaptic reflexes of the shank muscles via the subcortical pathway (Boroojerdi et al., 2000), the CCR of PL-SOL was unaffected during the SLR phase. In contrast to the SLR, the MLR is modulated by supraspinal structures via polysynaptic pathways (Gollhofer et al., 1989). While no influence of jaw clenching on the CCR of the shank and thigh muscles was noted, we detected a lower CCR in the TON group than in the other groups.

The increased platform displacement with time was compensated in the LLR phase, with most thigh muscles contributing to balance recovery (Freyler et al., 2015). The LLR is modulated under the involvement of corticospinal pathways (Taube et al., 2006). Boroojerdi et al. showed that jaw clenching led to marked facilitation of corticospinal pathways to the leg muscles (Boroojerdi et al., 2000). This might be the explanatory model for the observed higher CCR in the JAW and TON groups than in the HAB group during the LLR phase.

5.5.6 Limitations

First, all the participants were physically active, healthy adults. Accordingly, conclusions can only be made for this group. Secondy, this study used the oscillating Posturomed platform to evaluate the dynamic reactive balance performance. The Posturomed platform is commonly used in scientific studies (Freyler et al., 2015; Kiss, 2011a). However, it should be noted that balance performance outcomes under different dynamic balance conditions might not be fully comparable (Ringhof & Stein, 2018). Third, the participants were allocated into three groups with different oral-motor tasks. This could be considered a limitation because of possible baseline performance differences between groups. However, to overcome this problem, a baseline measurement was conducted in the habitual biting condition to match the three groups in terms of performance and sex. We found no baseline performance differences between the three groups ($p = 0.767$). One might think it would have been ideal if all subjects had performed all oral-motor tasks. However, “habitual” in this study meant that no instructions were given regarding the status of the masticatory organ. Therefore, an unconscious, ancestral behavioral pattern of the masticatory system during the balancing task could be expected. By definition, an “instructed” behavioral pattern can never correspond to an unconsciously performed behavior. An instructed “habitual” oral-motor behavior could result in dual-task effects, making it difficult to distinguish between cognitive and postural effects (i.e. thinking about the instructed behavior and performing various oral-motor tasks, respectively).

The three-group approach provided two main advantages. First, possible carry-over effects between different oral-motor tasks were avoided. For example, some physiological effects could have lingered after jaw clenching or tongue pressing, such as an increased motor system excitability or fatigue of the masticatory muscle system. Second, we would need 36 valid trials if all participants performed all three oral-motor tasks for each of the four directions. Considering the number of invalid trials, the total number of trials could result in fatigue, decreasing the data quality.

5.6 Conclusion and Outlook

We hypothesized that a neuromuscular mechanism that changes the CCR level of relevant muscle pairs was behind the improved performance during a dynamic reactive balancing task and concurrent jaw clenching, as shown for static conditions. Based on our results, this hypothesis must be rejected. The results did not explain the improved dynamic reactive balance under the influence of jaw clenching compared to tongue pressing or habitual oral behavior. Neither the iEMG nor CCR analysis helped to elucidate a general neuromuscular effect of jaw clenching on dynamic reactive balancing performance. Other analytical approaches seem necessary to investigate the causes of such an effect.

Based on a secondary finding, we hypothesize that tongue pressing causes an adjustment to the CCR of distal muscle groups based on changes in the biomechanical coupling between the head and trunk. The facilitation of corticospinal pathways under the influence of oral-motor activity seems to play a role only in later phases. This might indicate that robust fixed patterns of rapid postural responses during the important initial phases of balance recovery are present (Nashner, 1977).

6 Study III – Modulation of Jaw Clenching Effects after Jaw Clenching Training

Slightly modified[#] version of the paper published as

Fadillioglu, C., Kanus, L., Möhler, F., Ringhof, S., Hellmann, D., & Stein, T. (2023). Effects of jaw clenching on dynamic reactive balance task performance after 1-week of jaw clenching training. Frontiers in Neurology, *14*, 1-13. [*These authors have contributed equally to this work.]

[#]Table 6.1-3 were reshaped. The results were rounded to one decimal place.

6.1 Abstract

Introduction: Good balance is essential for human daily life as it may help to improve the quality of life and reduce the risk of falls and associated injuries. The influence of jaw clenching on balance control has been shown under static and dynamic conditions. Nevertheless, it has not yet been investigated whether the effects are mainly associated with the dual-task situation or are caused by jaw clenching itself. Therefore, this study investigated the effects of jaw clenching on dynamic reactive balance task performance prior to and after 1 week of jaw clenching training. It was hypothesized that jaw clenching has stabilizing effects resulting in a better dynamic reactive balance performance, and these effects are not related to dual-task benefits.

Methods: A total of 48 physically active and healthy adults (20 female, 28 male) were distributed into three groups, one habitual control group (HAB) and two jaw clenching groups (JAW, INT) that had to clench their jaws during the balance tasks at T1 and T2. One of those two groups, the INT group, additionally practiced the jaw clenching task for one week, making it familiar and implicit at T2. The HAB group did not receive any instruction regarding jaw clenching condition. Dynamic reactive balance was assessed using an oscillating platform perturbed in one of four directions in a randomized order. Kinematic and electromyographic (EMG) data were collected by using a 3D motion capture system and a wireless EMG system, respectively. Dynamic reactive balance was operationalized by the

damping ratio. Further, the range of motion of center of mass (CoM) in perturbation direction (RoM_{CoM_AP} or RoM_{CoM_ML}) as well as the velocity of CoM (V_{CoM}) in 3D were analyzed. The mean activity of the muscles relevant for perturbation direction were calculated to investigate reflex activities.

Results: The results revealed that jaw clenching had no significant effects on dynamic reactive balance performance or CoM kinematics in any of the three groups, and automation of jaw clenching in the INT group did not result in a significant change either. However, high learning effects, as revealed by the higher damping ratio values and lower V_{CoM} at T2, were detected for the dynamic reactive balance task even without any deliberate balance training in the intervention phase. In case of backwards perturbation of the platform, the soleus activity in short latency response phase increased for the JAW group, whereas it decreased for HAB and INT after intervention. In case of forwards acceleration of the platform, JAW and INT showed a higher tibialis anterior muscle activity level in medium latency response phase compared to HAB at T1.

Discussion: Based on these findings, it can be suggested that jaw clenching may lead to some changes in reflex activities. However, the effects are limited to anterior–posterior perturbations of the platform. Nevertheless, high learning effects may have overall overweighed the effects related to jaw clenching. Further studies with balance tasks leading to less learning effects are needed to understand the altered adaptations to a dynamic reactive balance task related to simultaneous jaw clenching. Analysis of muscle coordination (e.g., muscle synergies), instead of individual muscles, as well as other experimental designs in which the information from other sources are reduced (e.g., closed eyes), may also help to reveal jaw clenching effects.

6.2 Introduction

Balance is one of the essential aspects of postural control and is crucial to accomplish daily life activities, such as unassisted standing and walking. Impaired balance control may lead to an increased risk of falls and a reduced quality of life (Rubenstein, 2006; Shumway-Cook & Woollacott, 2017). From a mechanical point of view, balance involves controlling the center of mass (CoM) with respect to the base of support (Shumway-Cook & Woollacott, 2017). During standing, the CoM sways steadily within the body‘s base of support (i.e. static steady balance), whereas during perturbations stability needs to be recovered to bring the CoM back to allowed limits necessary for maintaining posture (i.e. dynamic reactive balance; (Hof et al., 2005). Given the importance of balance (Shumway-Cook & Woollacott, 2017), it is valuable to improve its control mechanisms by balance training.

This is recommended for performance enhancement in sports (Hrysomallis, 2011), to prevent injuries (Hrysomallis, 2007), and to decrease falls in at-risk groups (Sherrington et al., 2008, 2019).

An important prerequisite for balance is the sensory input that derives from somatosensory, visual and vestibular systems and provides the central nervous system (CNS) with information regarding the state of the body and the environment. This sensory information is weighted in a task-dependent manner (Peterka, 2002). For example, when the support surface is rapidly displaced (i.e. the dynamic reactive balance control is challenged), the CNS mostly relies on somatosensory inputs since these enable faster reactions than other systems of sensory input (Shumway-Cook & Woollacott, 2017). Given the importance of somatosensory information for dynamic reactive balance control, any alteration that improves dynamic stability may be relevant for fall prevention, especially in regards to unexpected external perturbations (Rubenstein, 2006; Winter, 1995).

A growing body of literature suggests that there is a close relationship between the stomatognathic system and balance (Alghadir et al., 2015a, 2015c; Allen et al., 2018; Fadillioglu et al., 2022a; Julià-Sánchez et al., 2015; Ohlendorf et al., 2014; Ringhof, Leibold, et al., 2015; Tomita et al., 2021; Zafar et al., 2020). The underlying mechanisms have not yet been fully understood, however, in various studies (Boroojerdi et al., 2000; Miyahara et al., 1996; Takada et al., 2000; Tuncer et al., 2007) it was shown that jaw clenching in a manner similar to the Jendrassik maneuver (Jendrassik, 1885) may lead to increased motor excitability , increased H-reflex responses. In addition, co-contraction behavior of the masticatory and neck muscles occurring as a result of complex neurophysiological interactions (Giannakopoulos, Schindler, et al., 2018) may also contribute to an improved postural control, for example via a more stable head or gaze position (Abrahams, 1977; Gangloff et al., 2000; Tanaka et al., 2006). These results are neuroanatomically supported by findings in animal models which found neuronal links of the trigeminal nerve to numerous brainstem nuclei and all levels of the spinal cord (Ruggiero et al., 1981).

Although jaw clenching has been shown to affect balance performance under both static (Hellmann et al., 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015) and dynamic conditions (Fadillioglu et al., 2022a; Tomita et al., 2021), it is still unknown whether these effects are associated with the dual-task situation (i.e. influences of simultaneously-performed additional motor tasks (Andersson et al., 2002; Broglio et al., 2005)) or those specifically connected to jaw clenching. In general, when two tasks are performed simultaneously, performance decreases in one or both tasks (R. A. Schmidt et al., 2018), which can be explained by the limited capacity of attention (Woollacott & Shumway-Cook, 2002). However, with respect to balance control, previous studies showed that combining a secondary task with a balance task may actually improve performance compared to single task condition (Broglio et al., 2005). This phenomenon can be explained by altered attention and increased automatization of balance control processes (Andersson et al., 2002; Wachholz et al., 2020). Therefore, one might argue that stabilizing effects on balance control could be caused by the secondary task of jaw clenching.

To sum up, the acute positive effects of jaw clenching have been shown in various studies (Fadillioglu et al., 2022a; Hellmann et al., 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015; Tomita et al., 2021), however it has not yet been evaluated if these effects are associated with dual-task benefits or specifically based on neurophysiological effects caused by jaw clenching. Therefore, this study established an intervention group (INT) that trained jaw clenching, so that it becomes an implicit task. The comparison with a group (JAW) that was only instructed in jaw clenching shortly before T1 and T2 and with a group without any training as well as instruction (HAB) should help to draw a firm conclusion about the above mentioned dual-task issue. It was hypothesized that jaw clenching has an effect on dynamic reactive balance and this effect is not related to dual-task benefits, which would be indicated by the missing differences in dynamic reactive balance performance between the INT and JAW groups at T2.

6.3 Methods

The study design comprised two measurement times (T1 and T2, separated by one week) and three groups (INT: intervention, JAW: jaw clenching and HAB: habitual), whose details can be found in the following sections. The data of two groups (JAW and HAB) at T1 were partially presented in previously published studies (Fadillioglu et al., 2022a, 2022b). An *a priori* power analysis was performed based on the study by Ringhof et al. (Ringhof, Stein, et al., 2015) that analyzed the effects of submaximal jaw clenching on postural stability. The results revealed that 16 participants per group would be sufficient to reach a power of > 0.8.

6.3.1 Participants

A total of 48 physically active adults (20 female, 28 male; age: 23.2 ± 2.4 years; height: 1.74 ± 0.09 m; body mass: 69.4 ± 10.4 kg) participated in this study. All participants gave written informed consent prior to the study, confirmed that they were participating in any kind of sports regularly at least three times per week and were naive to the balance task instrument. They had no muscular or neurological diseases, showed no signs or symptoms of temporomandibular disorders (based on the Research Diagnostic Criteria for Temporomandibular Disorders (Dworkin & LeResche, 1992)), and presented with full dentition (except for third molars) in neutral occlusion. The study was approved by the Ethics Committee of the Karlsruhe Institute of Technology.

6.3.2 Study design

To investigate whether the stabilizing effects of jaw clenching are merely a result of dual-task effects, the principal idea of our three-armed intervention study was that one of the groups, namely INT, repeatedly practiced jaw clenching to make it a familiar and implicit task. The details of the three different groups (INT, JAW and HAB) are shown in Figure 6.1.

Dynamic reactive balance performance was assessed by a commercially-available oscillating platform (Posturomed, Haider-Bioswing, Weiden, Germany), which has previously been used to systematically investigate dynamic reactive balance performance after perturbations in many other studies (Freyler et al., 2015; Kiss, 2011a; Pfusterschmied, Stöggl, et al., 2013). It is a rigid platform (12 kg, 60 cm × 60 cm) connected to a metal frame with eight steel springs (15 cm) of identical strength and can swing along the horizontal plane in all directions freely. A custom-made release system was used to apply mechanical perturbations in one of the four possible directions, back (*B*), front (*F*), left (*L*), right (*R*), in a randomized order (Fadillioglu et al., 2022a). Before the trials began, the participants were familiarized with the Posturomed by two trials without and two trials with perturbation. Afterwards, a baseline measurement with a perturbation was conducted in the habitual stomatognathic motor condition to determine initial balance performance (Fadillioglu et al., 2022a). Before each trial, participants were asked to stand on the platform on their dominant leg, hands at hips, eyes focusing on a fixed point at eye level horizontally 4 m away from the center of the platform and to compensate the perturbation as quickly as possible. Their dominant leg was determined based on self-reports or, in case of uncertainty, by testing on the Posturomed (Fadillioglu et al., 2022a; Ringhof & Stein, 2018). In each trial, the platform was perturbed by the release system unpredictably in one of the four possible directions in a randomized order. The release system was used to release the platform from its maximum displaced position along the perturbation axis. After the perturbation, no external resistance forces were applied and the participants had to dampen the perturbation by bringing the platform into its central position as soon as possible.

Both INT and JAW were jaw clenching groups and were instructed to clench their jaws during the balancing task. INT additionally trained in the jaw clenching task between T1 and T2, which were separated by one week. The purpose of this intervention was to make the novel jaw clenching task more automated, such that focused attention is reduced at T2. Groups were assigned considering the subjects' gender as well as their initial balance performance to ensure even distribution across the three groups. It was statistically confirmed that there were no baseline performance differences between the three groups (one-way ANOVA, p = 0.920).

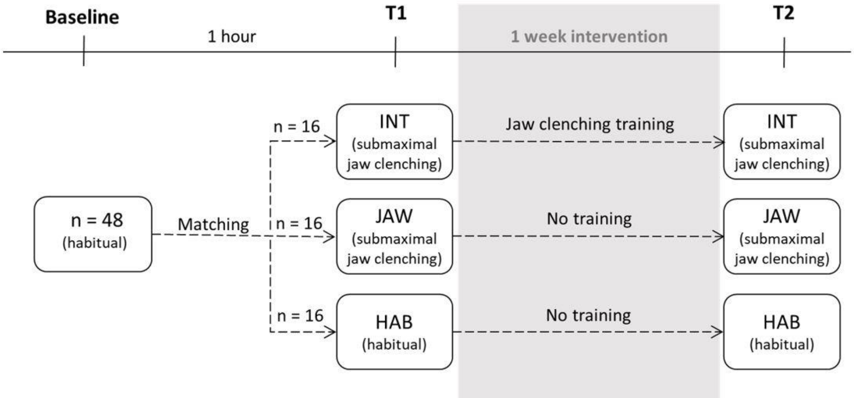

Figure 6.1: Study design (INT: intervention, JAW: jaw clenching, HAB: habitual, T1 and T2 are the measurement times).

During the balance task, INT and JAW were asked to clench their jaws with a force of 75 N. To familiarize with this task, participants trained for five minutes just before the measurements with a RehaBite® (Plastyle GmbH, Uttenreuth, Germany), a medical training device consisting of liquid-filled plastic pads, to get used to applying this level of force (Fadillioglu et al., 2022a; Giannakopoulos, Rauer, et al., 2018). During the measurements, the EMG activity of the masseter muscle corresponding to 75 N was used as reference and the participants in these two groups bit down on an Aqualizer® intra-oral splint (medium volume; Dentrade International, Cologne, Germany). HAB did not receive any instructions regarding the stomatognathic motor condition or an Aqualizer®. In the one-week intervention phase between T1 and T2, INT trained three times a day for 10 minutes (10 reps of 3 sets, applying force for 10 s, stretching the jaw muscles and resting for 10 s). For this purpose, the subjects received a RehaBite® and a diary to record the training sessions.

6.3.3 Measurements

A total of 22 anthropometric measures were manually taken from each participant and 42 reflective markers were placed on the participants' skin in accordance with the ALASKA modeling system (Advanced Lagrangian Solver in Kinetic Analysis, INSYS GmbH, Chemnitz, Germany (Härtel & Hermsdorf, 2006)) to capture full body kinematics. Four reflective markers were attached to the upper surface of the Posturomed platform (Fadillioglu et al., 2022a) and their displacements were captured using a 3D motion capture system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK; 10 Vantage V8 and 6 Vero V2.2 cameras; 200 Hz).

The activity of nine muscles (peroneus longus (PL), soleus (SOL), tibialis anterior (TA), rectus femoris (RF), semitendinosus (SM), rectus abdominis (AB), internal oblique (IO), erector spinae (ES) and masseter (MA)) were recorded using a wireless EMG system (Noraxon, Scottsdale, USA; 2000 Hz) at the standing leg side. Before the measurements, the skin over the relevant muscles was shaved, abraded and rinsed with alcohol. Bipolar Ag/AgCl surface electrodes (diameter 14 mm, center-to-center distance 20mm; Noraxon Dual Electrodes, Noraxon, Scottsdale, USA) were attached in accordance with the European Recommendations for Surface EMG (Hermens et al., 1999). Afterwards, maximum voluntary contraction (MVC) tests were performed for normalization. At T1, the positions of EMG electrodes were marked with a temporary tattoo ink, so that they could be placed on the same positions at T2.

A total of 12 valid trials (three per each of the four perturbation directions in a randomized order, each lasting 30 s) were recorded. Trials were invalid if participants did not apply enough force with their jaws (for INT and JAW), touched the ground with the non-standing foot, moved their standing foot or released their hands from the hip. The success rate was high (i.e. only 1-2 invalid trials per participant) and did not differ between the groups. At T1 and T2, the same measurement process was followed.

6.3.4 Data analysis

All data were recorded in Vicon Nexus 2.10 and processed with MATLAB R2021b (MathWorks). Kinematic data were filtered by a fourth-order Butterworth low-pass filter (10 Hz), and EMG data with a fourth-order Butterworth band-pass filter (10-500 Hz). The filtered EMG data were rectified, and normalized to the MVC amplitudes (Hellmann et al., 2015). *R* and *L* directions were re-sorted into ipsilateral (*I*) and contralateral (*C*) according to the standing leg of the participants.

To operationalize dynamic reactive balance performance, the damping ratio (Fadillioglu et al., 2022a; Kiss, 2011a) was calculated based on movement of the Posturomed using the data of the markers attached on the platform (Eq. 6.1, Figure 6.2). Larger damping ratio values represent better compensation of the perturbation, therefore better dynamic reactive balance, and *vice versa*. With respect to the EMG data, three main latency responses were considered after the onset of perturbation: short (SLR, 30 to 60 ms), medium (MLR, 60 to 85 ms), and long (LLR, 85 to 120 ms) (Freyler et al., 2015; Taube et al., 2006). Two further time windows were considered: 100 ms before the onset of perturbation (PRE, -100 to 0 ms) and after the reflex phases until the end of the individual damping ratio (DRP, 120 to 1136 ± 131 ms). Mean activities of the relevant muscles (directions *B*: PL & SOL; *F*: TA & AB; *I*: SM & IO, and *C*: RF & ES (S. M. Henry et al., 1998); additionally MA for all directions) were calculated for the five phases, that is PRE, SLR, MLR, LLR, and DRP.

$$\text{Damping ratio}_{\mathrm{i}} = \frac{\Lambda}{\sqrt{\Lambda_{\mathrm{i}}^2+4\pi^2}} \;;\; \Lambda_{\mathrm{i}} = \frac{1}{3}\ln\frac{\mathrm{K}_0}{\mathrm{K}_{\mathrm{i}}} \;,\; \mathrm{K}_{\mathrm{i}} : \mathrm{i}^{\mathrm{th}}\text{positive amplitude} \tag{6.1}$$

The marker trajectories in 3D were used to estimate the CoM trajectories with the full-body Dynamicus model (ALASKA, INSYS GmbH, Chemnitz, Germany (Härtel & Hermsdorf, 2006)). The COM displacement (Pohl et al., 2020) was calculated as the range of motion of CoM along the perturbation axis ($\mathrm{RoM}_{\mathrm{CoM\_AP}}$ for *B* and *F*, and $\mathrm{RoM}_{\mathrm{CoM\_ML}}$ for *I* and *C*). Further, the three-dimensional velocity of the CoM (V_{CoM}) (Alizadehsaravi et al., 2020) was calculated for each trial and averaged for the whole damping ratio time window (0 ms until the end of the individual damping ratio).

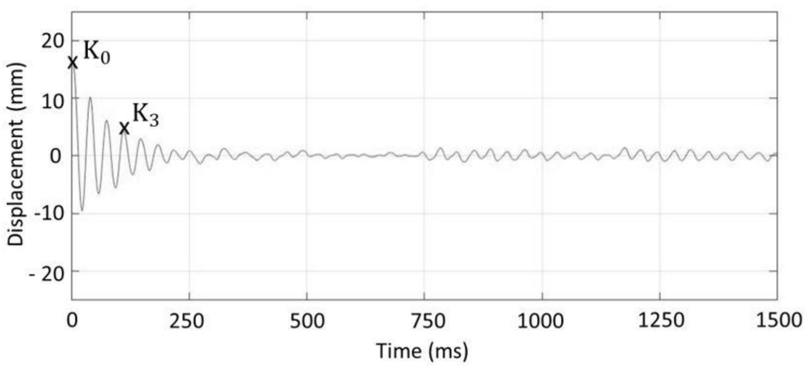

Figure 6.2: Calculation of damping ratio. The initial maximum displacement (K0) and the third positive amplitude (K3) were used for Eq. 6.1.

6.3.5 Statistics

Statistical calculations were done using IBM SPSS Statistics 25.0 (IBM Corporation, Armonk, NY, United States). For all dependent parameters (damping ratio, RoM_{CoM_AP}, RoM_{CoM_ML}, V_{CoM} and mean muscle activities) the three trials within each of the four perturbation directions were averaged. The normality of the data distributions was confirmed by Kolmogorov- Smirnov tests. The statistical assumptions were met to perform the repeated measures ANOVA (rmANOVA). The four perturbation directions were analyzed separately (Fadillioglu et al., 2022a) since it was suggested that the direction of surface translation influences the sensation, central processing and output of the postural responses differently (C. Chen et al., 2014; Nonnekes et al., 2013). For each dependent parameter, direction and phase, a rmANOVA was calculated with the factors group (INT, JAW and HAB) and time (T1 and T2). The significance level was set *a priori* to $p < 0.05$. In case of significant differences, *post-hoc* tests or t-tests were performed for pairwise comparisons. Partial eta-squared and Cohen's d were calculated to quantify the effect sizes for rmANOVA and *post-hoc* tests, respectively (small effect: $\eta_p^2 < 0.06$, $d < 0.50$; medium effect: $0.06 < \eta_p^2 < 0.14$, $0.5 < d < 0.8$; large effect: $\eta_p^2 > 0.14$, $d > 0.8$; (Cohen, 1988). The Bonferroni–Holm method was applied to correct the results for multiple comparisons (Holm, 1979).

6.4 Results

6.4.1 Dynamic reactive balance performance

The results regarding damping ratio for the four directions are illustrated in Figure 6.3. For the factor time, rmANOVA results revealed significant improvements in the directions *B*, *F* and *C* with high effect sizes (*B*: $p = 0.042$, $\eta_p^2 = 0.168$; *F*: $p = 0.015$, $\eta_p^2 = 0.206$; *C*: $p < 0.001$, $\eta_p^2 = 0.356$). However, there were no significant effects for the factor group as well as no interaction effects between the factors time and group. Accordingly, jaw clenching had no effect on dynamic reactive balance performance. In addition, the training of jaw clenching in the INT group did not show any effects on dynamic reactive balance performance. Independent of the groups, the dynamic reactive performance was better at T2 compared to T1.

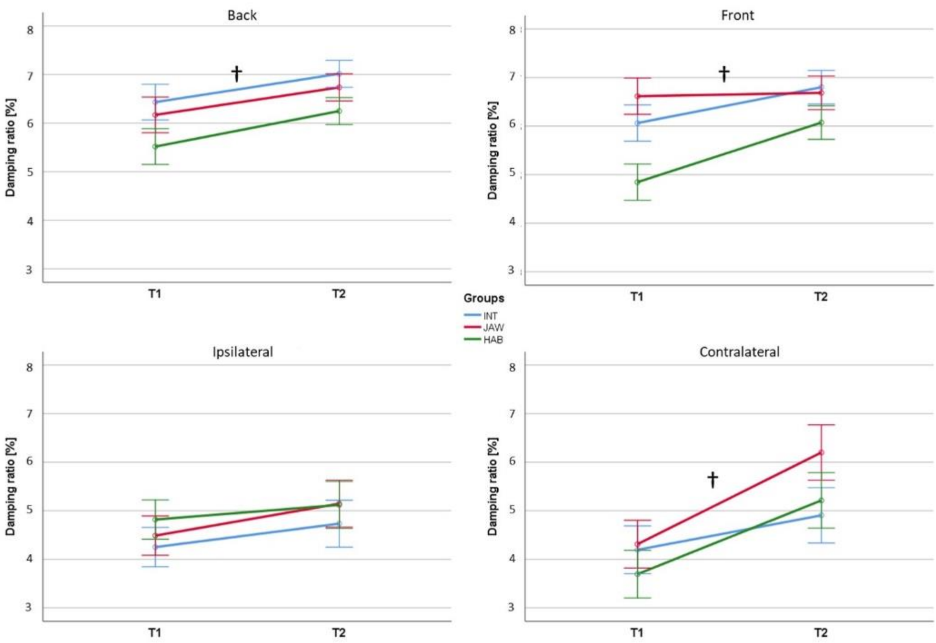

Figure 6.3: Damping ratio results. INT: intervention, JAW: jaw clenching, HAB: habitual. † signifies significant effects for the factor time. Significance level was set at $p < 0.05$.

6.4.2 Center of mass kinematics

The $\mathrm{RoM}_{\mathrm{CoM\_AP}}$, $\mathrm{RoM}_{\mathrm{CoM\_ML}}$ and V_{CoM} results for the four directions are represented in Figure 6.4a-b. $\mathrm{RoM}_{\mathrm{CoM\_AP}}$, $\mathrm{RoM}_{\mathrm{CoM\_ML}}$ did not show any significant effects. V_{CoM} had significant differences for the factor time in the directions *B*, *F, I* and *C* with high effect sizes (*B*: $p < 0.001$, $\eta_p^2 = 0.869$; *F*: $p = 0.004$, $\eta_p^2 = 0.289$; *I*: $p = 0.027$, $\eta_p^2 = 0.230$; *C*: $p = 0.037$, $\eta_p^2 = 0.220$). No significant effects for the factor group as well as no interaction effects between the factors time and group were detected. The results revealed that jaw clenching or its training had no significant effects on center of mass kinematics. Across the groups, the V_{CoM} decreased at T2.

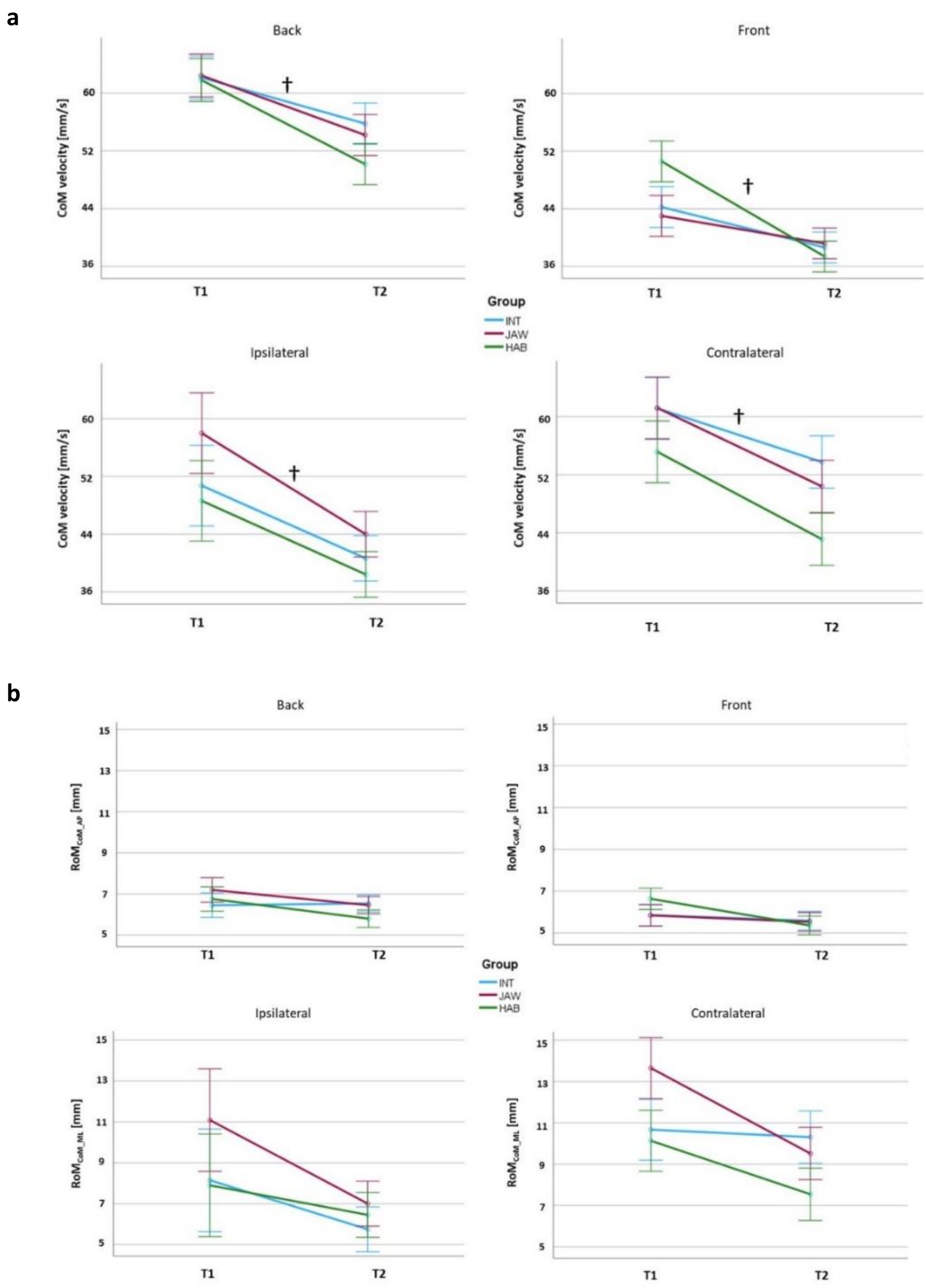

Figure 6.4: a. RoM_{CoM_AP}, RoM_{CoM_ML} results, b. V_{CoM} results. † signifies significant effects for the factor time.

6.4.3 Jaw clenching task controlled by masseter activity

Mean activities of the muscle MA for each phase are shown in Table 6.1. MA showed significant effects in all of the five phases for the factor time with medium effect sizes (PRE: $p < 0.001$, $\eta_p^2 = 0.133$; SLR: $p < 0.001$, $\eta_p^2 = 0.116$; MLR: $p < 0.001$, $\eta_p^2 = 0.106$; LLR: $p < 0.001$, $\eta_p^2 = 0.113$; DRP: $p < 0.001$, $\eta_p^2 = 0.121$) and for the factor group with high effect sizes (PRE: $p < 0.001$, $\eta_p^2 = 0.362$; SLR: $p < 0.001$, $\eta_p^2 = 0.364$; MLR: $p < 0.001$, $\eta_p^2 = 0.356$; LLR: $p < 0.001$, $\eta_p^2 = 0.351$; DRP: $p < 0.001$, $\eta_p^2 = 0.340$). In two of the five phases, there were significant interaction effects of the factors group and time with medium effect sizes (PRE: $p = 0.002$, $\eta_p^2 = 0.066$; SLR: $p = 0.003$, $\eta_p^2 = 0.061$). *Post-hoc* results showed that HAB had significantly lower MA activity with high effect sizes in all of the five phases in comparison to INT (PRE: $p < 0.001$, d = 1.268; SLR: $p < 0.001$, d = 1.260; MLR: $p < 0.001$, d = 1.240; LLR: $p < 0.001$, d = 1.229; DRP: $p < 0.001$, d = 1.225) as well as in comparison to JAW (PRE: $p < 0.001$, d = 1.674; SLR: $p < 0.001$, d = 1.681; MLR: $p < 0.001$, d = 1.641; LLR: $p < 0.001$, d = 1.621; DRP: $p < 0.001$, d = 1.599).

Table 6.1: Mean muscle activities for MA in the five phases for all perturbation directions. Significant effects are highlighted in bold. † signifies significant effects for the factor time, * for the factor group, and # the interaction effects. The significance level was set at $p < 0.05$.

		PRE	SLR	MLR	LLR	DRP
T1	INT	**6.4 ± 5.1*†#**	**5.5 ± 4.6*†#**	**5.2 ± 4.3*†**	**5.6 ± 4.7*†**	**6.5 ± 5.2*†**
	JAW	**6.0 ± 4.3*†#**	**5.2 ± 3.7*†#**	**5.0 ± 3.6*†**	**5.3 ± 3.8*†**	**6.2 ± 4.4*†**
	HAB	**1.2 ± 2.0*†#**	**1.0 ± 1.7*†#**	**1.0 ± 1.7*†**	**1.1 ± 1.9*†**	**1.4 ± 1.7*†**
T2	INT	**3.6 ± 3.0*†#**	**3.2 ± 2.6*†#**	**3.1 ± 2.5*†**	**3.3 ± 2.7*†**	**4.7 ± 5.2*†**
	JAW	**5.2 ± 3.1*†#**	**4.7 ± 2.9*†#**	**4.5 ± 2.8*†**	**4.8 ± 3.0*†**	**5.9 ± 3.6*†**
	HAB	**0.5 ± 0.7*†#**	**0.4 ± 0.7*†#**	**0.4 ± 0.7*†**	**0.4 ± 0.8*†**	**0.4 ± 0.3*†**

These results indicated, first, that the MA activity at T1 was higher than at T2 independent of the group. Secondly, the group HAB had significantly lower MA activity compared to both jaw clenching groups, INT and JAW, independent of the measurement time. Thirdly, the reduction in MA activity level from T1 to T2 was partly higher for the jaw clenching group, INT, that trained for the task between two measurement times compared to JAW and HAB.

6.4.4 Muscle activities in the critical phases for reflexes

Mean activities of the analyzed muscles for each phase are shown in Table 6.2 and Table 6.3 for anterio-posterior and medio-lateral perturbations, respectively. The significant effects are highlighted in the tables. The corresponding p-values and effect sizes are reported in the following paragraphs.

For the direction *B*, the muscle SOL showed significant interaction effects between the factors time and group with high effect sizes in SLR ($p = 0.002$, $\eta_p^2 = 0.240$). At T2, the group JAW had an increased level of SOL activity compared to T1, whereas the other two groups had a decreased level. For the direction *F*, the muscle TA showed significant effects with high effect sizes for the factor time in three of the five phases (PRE: $p < 0.001$, $\eta_p^2 = 0.269$; SLR: $p = 0.003$, $\eta_p^2 = 0.177$; DRP: $p < 0.001$, $\eta_p^2 = 0.333$) as well as for the factor group in one phase (MLR: $p < 0.001$, $\eta_p^2 = 0.306$). Across all groups the level of TA activity was decreased at T2 compared to T1 in PRE, SLR and DPR. Further, across the measurement times the JAW and INT groups had a higher level of TA activity compared to HAB in MLR. The *post-hoc* t-test results revealed that these differences were valid at T1, but not at T2. For the directions *C* and *I*, no significant effects were detected.

In summary, the results showed that the reflex activity changes were limited to anterior-posterior directions (*B* and *F*). In case of backwards acceleration of the platform, the JAW group showed increases in SOL activity at T2, whereas the other two groups revealed decreases. In case of forwards acceleration of the platform, the TA activity was lower at T2 compared with T1 in three reflex phases independent of the groups. Further, the two jaw clenching groups (JAW and INT) had higher TA activity compared to HAB in MLR phase at T1.

Table 6.2: Mean muscle activities for perturbation-relevant muscles in the five phases for anterio-posterior perturbations. Significant effects are highlighted in bold. † signifies significant effects for the factor time, * for the factor group, and # the interaction effects. The significance level was set at $p < 0.05$.

Back		PRE	SLR	MLR	LLR	DRP
PL						
T1	INT	14.4 ± 10.9	16.8 ± 16.8	17.2 ± 12.7	14.8 ± 10.7	22.6 ± 11.4
	JAW	21.1 ± 11.7	22.9 ± 16.0	21.0 ± 11.9	20.1 ± 11.8	26.5 ± 10.6
	HAB	37.5 ± 74.7	26.3 ± 35.1	44.5 ± 99.5	45.9 ± 103.2	37.2 ± 41.4
T2	INT	13.7 ± 9.7	17.7 ± 17.1	18.5 ± 18.1	19.5 ± 15.7	22.6 ± 14.4
	JAW	12.7 ± 6.8	16.2 ± 11.0	14.4 ± 9.1	17.2 ± 12.7	21.1 ± 10.2
	HAB	19.4 ± 18.6	20.9 ± 17.0	23.2 ± 30.0	22.1 ± 23.8	25.4 ± 18.6
SOL		**PRE**	**SLR**	**MLR**	**LLR**	**DRP**
T1	INT	19.6 ± 12.3	**21.2 ± 11.7#**	20.6 ± 24.1	21.8 ± 19.0	26.4 ± 13.6
	JAW	14.6 ± 6.7	**12.8 ± 6.2#**	15.4 ± 12.1	18.4 ± 12.8	21.8 ± 10.1
	HAB	16.2 ± 10.7	**16.9 ± 13.2#**	15.5 ± 16.5	13.0 ± 9.5	20.8 ± 11.6
T2	INT	15.3 ± 5.0	**13.7 ± 5.6#**	14.8 ± 11.0	18.4 ± 12.3	24.3 ± 15.2
	JAW	18.3 ± 7.4	**18.3 ± 9.5#**	14.3 ± 7.7	16.8 ± 10.1	23.6 ± 11.9
	HAB	12.9 ± 8.0	**11.4 ± 5.9#**	10.2 ± 4.8	12.9 ± 7.1	19.6 ± 9.4
Forward		**PRE**	**SLR**	**MLR**	**LLR**	**DRP**
TA						
T1	INT	**12.0 ± 13.0†**	**12.7 ± 15.9†**	**11.8 ± 11.3***	9.6 ± 8.3	**14.2 ± 5.8†**
	JAW	**9.6 ± 5.8†**	**10.6 ± 9.5†**	**10.9 ± 7.1***	9.6 ± 6.9	**15.4 ± 8.2†**
	HAB	**7.1 ± 5.3†**	**5.5 ± 4.0†**	**6.4 ± 4.1***	6.2 ± 3.9	**13.4 ± 7.3†**
T2	INT	**5.9 ± 7.9†**	**5.3 ± 5.8†**	**4.4 ± 3.7***	6.3 ± 5.1	**10.3 ± 6.4†**
	JAW	**6.0 ± 2.9†**	**5.2 ± 3.0†**	**5.4 ± 2.9***	5.8 ± 5.2	**9.7 ± 5.1†**
	HAB	**5.8 ± 2.8†**	**5.8 ± 3.8†**	**6.5 ± 5.7***	7.0 ± 4.5	**11.5 ± 5.9†**
AB		**PRE**	**SLR**	**MLR**	**LLR**	**DRP**
T1	INT	1.4 ± 2.1	1.5 ± 2.5	1.4 ± 2.0	1.4 ± 1.7	1.4 ± 1.6
	JAW	0.9 ± 0.6	0.9 ± 0.8	0.7 ± 0.4	1.0 ± 0.7	1.1 ± 0.7
	HAB	1.1 ± 1.1	1.2 ± 1.1	1.1 ± 1.1	0.9 ± 0.8	1.4 ± 1.2
T2	INT	0.9 ± 1.4	0.9 ± 1.5	0.8 ± 1.1	0.8 ± 1.2	1.1 ± 1.6
	JAW	0.9 ± 0.7	0.8 ± 0.7	0.8 ± 0.6	0.9 ± 0.9	0.9 ± 0.7
	HAB	1.3 ± 1.0	1.1 ± 1.0	1.2 ± 0.9	1.3 ± 1.0	1.3 ± 0.8

Table 6.3: Mean muscle activities for perturbation-relevant muscles in the five phases for medio-lateral perturbations.

Ipsilateral		PRE	SLR	MLR	LLR	DRP
SM						
T1	INT	5.0 ± 5.5	7.2 ± 9.6	6.3 ± 9.7	6.1 ± 8.2	7.9 ± 7.7
	JAW	3.9 ± 3.4	3.5 ± 3.5	4.5 ± 4.1	4.1 ± 3.2	5.8 ± 4.9
	HAB	5.0 ± 4.4	4.6 ± 4.0	4.7 ± 4.3	5.2 ± 4.9	6.7 ± 5.9
T2	INT	4.1 ± 6.9	3.9 ± 5.5	4.5 ± 7.1	4.8 ± 8.8	6.5 ± 8.5
	JAW	3.1 ± 2.4	3.0 ± 3.0	3.6 ± 3.1	3.8 ± 3.2	4.1 ± 2.5
	HAB	3.9 ± 5.1	4.0 ± 5.5	4.6 ± 5.8	4.3 ± 5.8	5.7 ± 7.0
IO		PRE	SLR	MLR	LLR	DRP
T1	INT	2.8 ± 2.7	3.3 ± 3.3	2.9 ± 3.1	3.2 ± 3.5	3.7 ± 3.1
	JAW	2.7 ± 1.5	2.7 ± 1.7	2.5 ± 1.3	2.6 ± 1.4	3.5 ± 1.5
	HAB	2.2 ± 1.2	2.2 ± 1.3	2.2 ± 1.3	2.1 ± 1.0	3.9 ± 3.1
T2	INT	1.9 ± 1.8	2.6 ± 2.0	2.7 ± 2.4	2.7 ± 2.9	3.3 ± 2.3
	JAW	1.9 ± 1.6	2.5 ± 2.2	2.6 ± 2.6	2.8 ± 2.5	3.3 ± 2.1
	HAB	2.1 ± 1.4	1.8 ± 1.5	1.9 ± 1.2	2.0 ± 1.3	2.8 ± 2.1
Contralateral		PRE	SLR	MLR	LLR	DRP
RF						
T1	INT	2.3 ± 4.3	3.8 ± 2.8	4.8 ± 8.3	4.5 ± 7.3	5.3 ± 3.9
	JAW	3.8 ± 2.3	5.4 ± 4.4	3.6 ± 2.5	4.7 ± 2.9	6.2 ± 3.9
	HAB	2.7 ± 2.7	2.5 ± 2.0	2.9 ± 2.9	2.9 ± 2.6	4.8 ± 4.9
T2	INT	3.0 ± 3.0	3.3 ± 3.3	3.1 ± 3.1	3.3 ± 3.6	5.2 ± 5.6
	JAW	3.4 ± 3.3	3.3 ± 3.1	3.6 ± 3.8	3.9 ± 4.2	5.0 ± 3.9
	HAB	2.6 ± 2.0	2.6 ± 2.2	2.4 ± 1.8	2.6 ± 1.6	4.2 ± 2.7
ES		PRE	SLR	MLR	LLR	DRP
T1	INT	5.1 ± 3.2	5.2 ± 3.1	6.8 ± 5.6	7.2 ± 6.5	7.9 ± 5.1
	JAW	4.6 ± 4.9	4.1 ± 4.3	4.7 ± 4.8	4.8 ± 3.8	8.1 ± 7.9
	HAB	4.3 ± 3.4	4.7 ± 4.0	5.7 ± 7.5	4.3 ± 3.3	8.1 ± 7.1
T2	INT	7.0 ± 6.4	5.7 ± 3.9	7.2 ± 7.7	6.8 ± 6.9	10.2 ± 8.1
	JAW	4.4 ± 3.6	4.1 ± 3.1	4.5 ± 4.0	4.8 ± 4.7	6.2 ± 4.5
	HAB	4.8 ± 3.4	4.6 ± 3.9	4.2 ± 3.0	4.4 ± 3.4	7.0 ± 5.2

6.5 Discussion

The aim of this study was to investigate the effects of jaw clenching training on a dynamic reactive balance task performance after 1 week of jaw clenching training. It was hypothesized that jaw clenching has stabilizing effects resulting in better dynamic reactive balance performance and these effects persist at T2 after intervention. This would mean that these improvements are not a result of the dual-task effect, but are specifically associated with jaw clenching. The results indicated that neither jaw clenching nor its automation through training resulted in significant dynamic reactive balance performance differences. However, independent of the groups, the dynamic reactive balance performance was better at T2 compared to T1. As there was not any deliberate balance training in the intervention phase, this result is indicative of high learning effects. Further, jaw clenching may lead to some changes in reflex activities but they are limited to anterior-posterior perturbation of the platform.

6.5.1 Effects of jaw clenching on dynamic reactive balance performance and CoM kinematics

Dynamic reactive balance performance was operationalized by the damping ratio as in other studies (Fadillioglu et al., 2022a; Kiss, 2011a). In addition, the RoM of CoM along the perturbation axis as well as V_{CoM} were calculated. In all of the directions, no significant effects due to jaw clenching were observed. Previous studies showed that jaw clenching may affect balance performance under static steady-state conditions (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015), as well as under dynamic conditions (Fadillioglu et al., 2022a; Tomita et al., 2021). However, the nature of these effects is still unknown and could be associated with the dual-task situation. To the best of our knowledge, research so far has not addressed this point explicitly. This study investigated the effects of jaw clenching on dynamic reactive balance performance after 1 week of jaw clenching training to determine if the effects are a result of the general dual-task situation or specifically due to neurophysiological effects of jaw clenching. At T1 and T2, both INT and JAW groups were instructed to do the same dual-task. These two groups differed only in the intervention: INT trained the jaw clenching task, whereas JAW did not. It was assumed that after one week of training (18 training sessions á 10 minutes of practice), the participants of INT would be able to fulfill the jaw clenching task in an automated manner. Therefore, it was hypothesized that the INT group would have reduced focused attention on the secondary jaw clenching task (Andersson et al., 2002) and therefore a worse balance performance than JAW at T2. However, the results did not reveal any significant performance differences between the groups. Based on this it can be concluded that the jaw clenching task did not have any observable effects on dynamic reactive balance performance, which was operationalized by the damping ratio and CoM kinematics. Further, its automation also did not result in any significant changes. On the other hand, another explanation might be that the response of the motor system to the complexity of the present balance task possibly masked the effects of jaw clenching, which were identified in previous experiments with static balance tasks (Hellmann et al., 2015; Ringhof, Stein, et al., 2015). In addition, in a previous study by Tardieu et al. (Tardieu et al., 2009), the effects of dental occlusion on postural control was investigated both in eyes open and closed conditions. They reported that the sensory information associated with the dental occlusion becomes more important when the other sensory cues become scarce (e.g., eyes closed). On this basis, it can be suggested that jaw clenching task might potentially be beneficial once sensory information from other sources reduces. Nevertheless, in this study the balance task was performed with open eyes since the Posturomed task was too difficult to be handled with eyes closed.

6.5.2 High learning effects even without training between sessions

In three of four directions (*B*, *F* and *C*), dynamic reactive balance performance was improved at T2 even though the participants did not perform any balance training between T1 and T2. Further, in all directions V_{CoM} decreased significantly at T2, whereas the $\text{RoM}_{\text{CoM\_AP}}$, $\text{RoM}_{\text{CoM\_ML}}$ were not affected. It should be noted that the participants performed familiarization trials before the real measurements as in similar studies (Freyler et al., 2015; Petró et al., 2018). Further, within the individual measurement session there were no systematic performance improvements in terms of dynamic reactive balance. These results indicate that learning effects occurred without deliberate balance training for this specific task. Subsequently, the question arose if the learning effects were so large that they outweighed the possible effects of jaw clenching. With this study design, this question cannot be answered and further studies are needed. From the findings of this study it can be concluded that the used balance task used here shows high learning effects and is rather unsuitable for studies in which low intervention effects on balance performance are expected. In the present case as well as in similar cases, care should therefore be taken to select a balance task that shows only low learning effects or a longer intervention period should be scheduled between T1 and T2 to mitigate the unwanted learning effects.

The results also revealed that the velocity of the CoM changed but its RoM in the perturbation direction did not change at T2. This may be explained by the deceased CoM movement in case of the better damping of the platform by the participants, since the CoM is one of the controlled variables as suggested in postural studies (Richmond et al., 2021; Winter et al., 1998). On the other hand, the RoM_{CoM_AP}, RoM_{CoM_ML} depended for the most part on the initial maximum displacement of the platform, which was identical both at T1 and T2. Therefore, the RoM did not change at T2.

6.5.3 Changed muscular activity levels at T2

The results regarding muscle activities in reflex phases revealed that in case of the backwards perturbation of the platform (*B*), the SOL activity of JAW increased, whereas that of the other two groups decreased at T2 in the SLR phase. It is important to add that SOL is one of the most important muscles that help to restore equilibrium in response to posterior translations (S. M. Henry et al., 1998). This result may be interpreted as a difference between INT and JAW groups and it can be suggested that the jaw clenching task resulted in an increased muscle activity in SOL at T2, but these effects were not visible when the jaw clenching task became an implicit task and therefore lost its novelty (e.g., for the group INT). In addition, in case of forwards acceleration of the platform, TA activity of the both jaw clenching groups (INT and JAW) was overall higher compared to that of HAB in the MLR phase at T1. This finding contradicts the initial hypothesis that the jaw clenching task results in changes in reflex activities and these effects persist after 1 week of jaw clenching training. Nevertheless, these results are only limited to this perturbation direction and to this specific reflex phase. Furthermore, these changes did not cause any effects on dynamic reactive balance performance (i.e. damping ratio results).

In response to anterior surface translations, TA contracts to counteract the torques at the ankle and therefore helps to restore equilibrium (S. M. Henry et al., 1998). The TA activity decreased at T2 in three phases (PRE, SLR and DRP) across the groups, parallel to dynamic balance performance improvements. These results indicate that in case of forwards acceleration of the platform, a better performance at T2 is possibly related with a decreased TA activity. In general, significant changes were detected only for the anterior-posterior perturbation directions. Based on these results, it can be suggested that the jaw clenching task may result in changed muscle activity patterns, as observed with the alterations in certain muscle activities in the reflex phases, but changes seem to be direction-dependent as well as muscle dependent. This task specificity can be explained by the different postural responses to different perturbation directions (C. Chen et al., 2014; Kiss, 2011b; Nonnekes et al., 2013).

Further, it should be noted that the muscle activity changes and the dynamic balance performance differences did not show a common pattern for all directions (e.g., no changes in muscle activity levels in perturbation direction *C*, despite the improvements in dynamic reactive balance performance at T2). This may also possibly have been caused by the selection of the posture relevant muscles. Posture and its control are the product of intermuscular coordination patterns. Determining the activity of individual muscles might be the limiting factor in the analysis presented here. In light of these aspects, the question arises if mean muscle activities for the critical phases were sensitive enough to reveal changes on a muscular level. Nevertheless, these parameters were used in similar studies (e.g., iEMG in Freyler et al. (2015) and Pfusterschmied, Stöggl, et al. (2013)). In the present study, mean muscle activity was preferred since DRP was not the same length for each trial or participant. It was expected that increased level of reflex activities would be manifested by an increased level of muscle activities (Ertuglu et al., 2018). However, potentially jaw clenching effects are seen less in a changed level of individual muscle activities and more in a changed interplay of different muscles. Therefore, in future studies the coordination of different muscles should be analyzed in addition to the analysis of the activity of individual muscles. Coordination models such as muscle synergies are particularly suitable for this purpose (Munoz-Martel et al., 2021; Ting & Macpherson, 2005).

6.5.4 Jaw clenching task controlled by masseter activity

The EMG results indicate that the activity of the MA was higher for the groups INT and JAW compared to HAB. This suggests that the majority of the subjects in HAB, who did not receive instructions regarding activity of the stomatognathic system, had their jaws in the physiologically expected resting position (lips closed, teeth out of contact). It should be noted that the participants of JAW and INT trained immediately before starting the balancing task measurements with the Rehabite® device, so that they are able to apply a force at a level of 75 N consistently without feedback. The higher reduction in MA activity between T1 and T2 in the INT group compared with the other groups can be attributed to the training during the intervention phase. Similar effects were also shown in a previous study (Hellmann et al., 2011b), in which short-term force-controlled biting on a hydrostatic system caused long-term training effects.

A force of 75 N is easy to achieve for the stomatognathic system, as normal masticatory activities are in the range of this force level. The RehaBite®-training in the group INT between T1 and T2 was used to turn a novel, unfamiliar task (biting on a hydrostatic system is not part of the common functional repertoire of the stomatognathic system) into an implicit behavior so that it would not require additional attention during the balancing task. Therefore, RehaBite®-training between T1 and T2 in INT was not used to train the masticatory muscles but to address a potential dual-task effect during the balance task. It should also be noted that the jaw clenching task in this study is a different stomatognathic activity than daily chewing activity occurring when eating (Hellmann et al., 2011b). During the sub-maximum jaw clenching task, a force of 75 N was applied continuously, whereas during chewing an alternating force is applied. On this basis, it can be assumed that the deliberate jaw clenching task was novel to the participants at the first measurements. Further, it was also shown that the chewing task had no significant effects on body sway reduction during upright standing, whereas feedback- controlled jaw clenching task had (Hellmann et al., 2011a). This also supports that the sub-maximum jaw clenching and the chewing tasks are not the same task and they may lead to different neurophysiological effects.

6.5.5 Limitations

This study had some limitations: Firstly, even though the participants did not train for the balance task, learning effects occurred in three of the four directions independent of the group. These high learning effects may have outweighed the potential effects of jaw clenching. For future studies, more care should be taken to minimize possible learning effects. Secondly, all the participants were physically active and healthy adults, therefore potentially good at balancing. The same results may not be seen in groups with compromised postural control such as the elderly (M. Henry & Baudry, 2019) or people with neurological disorders (Xia & Mao, 2012). In future studies, the participants with poorer postural control might reveal effects of jaw clenching. Thirdly, the onset of the reflex phases was defined based on Posturomed movement but not on muscle activity peaks (Taube et al., 2006) or ankle movements, since there were no clear peaks in the EMG or kinematics data. Finally, the group HAB did not receive any instructions regarding stomatognathic activities. Self-administative questionnaires regarding the clenching habit would have been useful to collect habitual status.

6.6 Conclusion and Outlook

This study investigated the effects of jaw clenching on dynamic reactive balance task performance after 1-week of jaw clenching training, to examine if the effects are a result of a dual-task situation. Both jaw clenching and automation of the jaw clenching task seemed not to have any observable effects on dynamic reactive balance performance, but jaw clenching seemed to be related with some changes in reflex activities. However, these effects were limited to anterior-posterior perturbations. Further studies containing other balance tasks with less learning effects as well as with longer intervention periods are needed. Analysis of muscle coordination as well as other experimental designs with reduced sensory information from other sources (e.g., closed eyes) may also help to reveal jaw clenching effects.

7 Study IV – Modulation of Center of Mass Movement

Published as

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7.1 Abstract

Multiple sensory signals from visual, somatosensory and vestibular systems are used for human postural control. To maintain postural stability, the central nervous system keeps the center of mass (CoM) within the base of support. The influence of the stomatognathic motor system on postural control has been established under static conditions, but it has not yet been investigated during dynamic steady-state balance. The purpose of the study was to investigate the effects of controlled stomatognathic motor activity on the control and stability of the CoM during dynamic steady-state balance. A total of 48 physically active and healthy adults were assigned to three groups with different stomatognathic motor conditions: jaw clenching, tongue pressing and habitual stomatognathic behavior. Dynamic steady-state balance was assessed using an oscillating platform and the kinematic data were collected with a 3D motion capturing system. The path length (PL) of the 3D CoM trajectory was used for quantifying CoM sway. Temporal dynamics of the CoM movement was assessed with a detrended fluctuation analysis (DFA). An uncontrolled manifold (UCM) analysis was applied to assess the stability and control of the CoM with a subject-specific anthropometric 3D model. The statistical analysis revealed that the groups did not differ significantly in PL, DFA scaling exponents or UCM parameters. The results indicated that deliberate jaw clenching or tongue pressing did not seem to affect the sway, control or stability of the CoM on an oscillating platform significantly. Because of the task-specificity of balance, further research investigating the effects of stomatognathic motor activities on dynamic steady-state balance with different movement tasks are needed. Additionally, further analysis by use of muscle synergies or co-contractions

may reveal effects on the level of muscles, which were not visible on the level of kinematics. This study can contribute to the understanding of postural control mechanisms, particularly in relation to stomatognathic motor activities and under dynamic conditions.

7.2 Introduction

Balance maintenance and proper body orientation in space are essential for human life. They require a good, reliable and flexible postural control system which is capable of processing multiple sensory feedback inputs from the visual, somatosensory and vestibular systems in the spinal and supraspinal structures of the central nervous system (CNS) in a task dependent manner (Takakusaki, 2017). The control of posture involves control of the body position in space for stability and orientation. Stability is defined as the control of the center of mass (CoM) in relation to the base of support, whereas orientation refers to the ability to maintain an appropriate relationship between the body segments as well as between the body and the environment (Shumway-Cook & Woollacott, 2017). A healthy motor control system modulates the postural movements continuously as a function of the changing tasks. The inability to modulate postural sway, but also environmental or individual constraints may lead to poor performance, instability and falls (Haddad et al., 2013). Furthermore, it has been shown that improved postural control is associated with a decreased risk of falls (Horak, 2006; Rubenstein, 2006) as well as a decreased risk of injury (Hrysomallis, 2007).

Attentional processing is required during postural tasks; therefore, they may reduce the performance of a secondary task when performed simultaneously. On the other hand, a secondary task may improve the postural control by an improved automaticity, an increased arousal or through the utilization of reduced sway for the sake of a better supra-postural task performance (Shumway-Cook & Woollacott, 2017). Previous studies showed that postural control may be influenced by several factors, including motor activity in the stomatognathic motor system (Julià-Sánchez et al., 2020). A frequently cited explanation for this is based on the stimulation of periodontal mechano- receptors that are centrally integrated along with other sensory input and, therefore, facilitates the excitability of the human motor system (Boroojerdi et al., 2000) in a manner similar to the Jendrassik maneuver (Jendrassik, 1885), which in turn increases the neural drive to the distal muscles (Ebben, 2006; Ebben et al., 2008). A variety of studies indicated that stomatognathic motor activity in the form of chewing, tongue activity or different clenching conditions affects human balance and posture under static conditions (Alghadir et al., 2015c; Gangloff et al., 2000; Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015; Sakaguchi et al., 2007). Among others, a reduced body sway in the anterior- posterior direction (Hellmann et al., 2011a), a reduced variability of muscular co-contraction patterns of posture-relevant muscles of the lower extremities (Hellmann et al., 2015), and reduced trunk and head sway under the influence of controlled biting activities were reported during upright standing (Ringhof, Stein, et al., 2015). Furthermore, the review by de Souza et al. (2021) reported that jaw clenching during activities that involve the lower and upper limbs enhance neuromotor stimulation in terms of increased H-reflexes (Miyahara et al., 1996) and stimulate a larger area of the brain. Specifically, a large amount of activity was observed over the frontal, parietal, and temporal cortices and cerebellum during hand grip combined with jaw clenching compared to without jaw clenching (Kawakubo et al., 2014). The authors suggested that the stomatognathic motor system may have effects on the function of remote muscles via cortical activations. Furthermore, a higher excitability of the human motor system during voluntary jaw clenching has also been shown (Boroojerdi et al., 2000). From an evolutionary perspective, it was hypothesized that jaw clenching increases the blood flow to anterior temporal lobe structures during acute activation of the limbic fear circuits (Bracha, Ralston, et al., 2005). Jaw clenching may increase the blood flow to temporal lobe structures by pumping blood through the temporal bone emissary veins, thus conferring a possible survival advantage during activation of the limbic fear-circuits in expectation of situations requiring the freeze, flight, fight, fright acute fear response (Bracha, Bracha, et al., 2005). Stomatognathic motor activity also seems to be part of a common physiological repertoire used to improve motor performance during balance recovery tasks (Ringhof et al., 2016). Besides all these facts, it should be mentioned that it stomatognathic motor activity might be of clinical relevance for the prevention of falls. In elderly people there is evidence for an increased risk of falling resulting from an insufficient dental or prosthetic status (Mochida et al., 2018; Okubo et al., 2010).

In contrast to balance under static conditions (e.g., sitting or standing), the influence of stomatognathic motor activity under dynamic conditions (e.g., standing on a balance board or on an oscillating platform) has not yet been investigated in detail (Ringhof et al., 2016). Since the effects found during one balance task may not necessarily be transferable to another balance task (Giboin et al., 2015; Kümmel et al., 2016; Ringhof & Stein, 2018), the question arises whether the effects of stomatognathic motor activity found during static balance tasks would also be observable during dynamic ones. Accordingly, we started to investigate the effects of stomatognathic motor activity in the form of jaw clenching and tongue pressing on dynamic reactive balance performance (Fadillioglu et al., 2022a). This was realized by use of an oscillating platform perturbed randomly in one of four horizontal directions. In our previous study, the focus was on the first reactive part of the task. We showed that jaw clenching improved dynamic reactive balance in a task-specific (i.e. direction-dependent) way. The performance improvements found for jaw clenching were associated with lower mean speeds of distinct anatomical regions compared to both the tongue pressing and habitual groups. Subsequent to these findings, the question arises as to whether this performance increase is associated with a changed sway, stability or control of the CoM in the steady-state phase of the task.

The CoM is suggested to be the controlled variable in postural studies (Kilby et al., 2015; Nicolai & Audiffren, 2019; Richmond et al., 2021; Winter et al., 1998), although experimental verification is difficult (Shumway-Cook & Woollacott, 2017). Scholz et al. (2007) used an uncontrolled manifold (UCM) approach to determine if the CoM is the variable which is primarily controlled by the CNS during postural control. They showed that during recovery from a loss of balance, the participants tend to re-establish the position of the CoM rather than those of the joint configurations (Shumway-Cook & Woollacott, 2017), and therefore suggested that the CoM is the key variable controlled by the CNS. In postural control studies, CoM sway is an important parameter (Richmond et al., 2021) and its spatial dynamics can be quantified among others by the total distance covered (Prieto et al., 1996; Richmond et al., 2021). Another important aspect is the temporal dynamics of the sway, since variations in “supra-postural” activities may lead not only to spatial but also to temporal changes (F. C. Chen & Stoffregen, 2012). It was suggested that a detrended fluctuation analysis (DFA) can reveal the temporal dynamics of postural data, specifically to quantify the long-range correlations (or fractality) of the data (Duarte & Sternad, 2008; McGrath, 2016).

When controlling the body during balance tasks, the CNS has to coordinate a redundant musculoskeletal system (Bernstein, 1967) possessing more degrees of freedom than necessary to achieve the given task (Latash et al., 2002). Different approaches have been suggested to analyze how the CNS treats this redundancy, such as motor programs (R. A. Schmidt et al., 2018), optimal control (Todorov & Jordan, 2002) or synergies (D’Avella et al., 2003; Latash et al., 2007; Stetter et al., 2020). Latash et al. (2007) define “synergy” as a neural organization consisting of a multi-element system that organizes sharing of a task among a set of elemental variables (EVs), and ensures the stabilization of a performance variable (PV) through the co-variation of EVs. The fact that different combinations of EVs may result in the same PV indicates that the co-varied behavior provides flexibility for the system. In this context, redundancy is considered not as a problem but as an advantage for the motor control system. According to the motor abundance principle (Gelfand & Latash, 1998), redundancy in the motor control system can be considered positive since the co-variation at the level of the EVs may provide robustness against perturbations (Gera et al., 2010).

The UCM approach (Scholz & Schöner, 1999) is one possibility to quantify the amount of equivalent movement solutions and the degree of stability of the PV. The UCM approach requires a model that relates the changes in EVs to changes in the PV; and ultimately the effects of changes in EVs on the PV are analyzed (Scholz & Schöner, 2014). Both the EVs and PV are chosen on a physiological basis with task-specific considerations. The variability in EVs that results in a changed PV is quantified by the $UCM_{\perp}$ component, whereas it is associated with the $UCM_{\parallel}$ component if the PV remains the same even if the EVs vary over repetitions (Latash et al., 2007; Scholz & Schöner, 1999). The UCM approach has been applied to analyze various motor tasks; for example, reaching and pointing (Domkin et al., 2005; Tseng et al., 2002), pistol shooting (Scholz et al., 2000), sit-to-stand (Reisman et al., 2002; Scholz et al., 2001), parkour jumps (Maldonado et al., 2018), treadmill walking (Qu, 2012; Verrel et al., 2010) and running (Möhle et al., 2019). Kinematic or kinetic data were commonly used as EVs to investigate their effects on the PVs. There is also a number of studies that apply UCM to postural tasks (Freitas et al., 2006; Hagio et al., 2020; Hsu et al., 2007, 2013; Krishnamoorthy et al., 2005). When analyzing postural tasks, the CoM is typically chosen as the PV and joint angles as EVs (Freitas et al., 2006; Hagio et al., 2020; Hsu et al., 2013, 2017; Krishnamoorthy et al., 2005; Scholz et al., 2007). By means of UCM analysis, changes in the variability of coordinated joint movements in association with the stability and control of the CoM have been investigated for various setups with different research questions. In line with the previous studies, a UCM analysis was conducted in this study with stomatognathic motor conditions as the independent variable.

The aim of this study was to investigate the influence of different stomatognathic motor activities (jaw clenching and tongue pressing) on the sway, stability and control of the CoM during a dynamic steady-state balance task (one-legged standing on an oscillatory platform after perturbation). The path length (PL) of the 3D CoM was used to quantify the possible effects of different stomatognathic motor activities on the spatial dynamics of CoM sway, whereas its temporal dynamics was assessed with a DFA. A UCM approach was applied to investigate if and how the co-variation of the joint movements led to the stabilization and control of the CoM, which were quantified by UCM_{Ratio} and $UCM_{\perp}$, respectively. Following the results of our above-mentioned study on the influence of jaw clenching and tongue pressing on dynamic reactive balance performance (Fadillioglu et al., 2022a), it was hypothesized that these activities decrease the sway and increase the control and stability of the CoM. Therefore, a decreased PL of the CoM trajectory, an increased alpha of DFA, an increased UCM_{Ratio} and a decreased $UCM_{\perp}$ for the jaw clenching group (JAW) and the tongue pressing group (TON) compared to the group with habitual stomatognathic behavior (HAB) were expected. The findings of this study may contribute to the understanding of postural control, particularly in relation to stomatognathic motor activities and under dynamic conditions.

7.3 Methods

This study comprised a follow-on analysis of the original data set used in Fadillioglu et al. (2022a). In the previous study, the reactive phase of the task was analyzed, whereas in the present one, the following steady-state phase is investigated. An a priori power analysis was performed based on the findings of the study (Ringhof, Stein, et al., 2015) which analyzed the effects of submaximal jaw clenching on postural stability and on the kinematics of the trunk and head. The analysis revealed that 16 participants per group would be enough to reach the sufficient power (>0.8).

7.3.1 Participants

Forty-eight healthy adults (25 female, 23 male; age: 23.8 ± 2.5 years; height: 1.73 ± 0.09 m; body mass: 69.2 ± 11.4 kg) voluntarily participated in the study after giving written informed consent. All participants completed a questionnaire, confirmed that they were physically active (physical activity 4.6 ± 1.5 days/week and 436 ± 247 min/week) and naive to the tasks on an oscillating platform; had no muscular or neurological diseases; no signs and symptoms of temporomandibular disorders (assessed by means of the RDC/TMD criteria, (Dworkin & LeResche, 1992)). They presented in good oral health with full dentition (except for 3rd molars) in neutral occlusion. The study was approved by the Ethics Committee of the Karlsruhe Institute of Technology.

7.3.2 Experimental procedure

7.3.2.1 Balance tasks

Dynamic steady-state balance was assessed by means of a Posturomed oscillating platform (Haider-Bioswing, Weiden, Germany), which is a widely-used commercial device to analyze or improve dynamic balance in scientific studies as well as in physiotherapy (Freyler et al., 2015; Kiss, 2011a). It consists of a rigid platform (12 kg, 60 cm × 60 cm) connected to the main frame by eight 15 cm steel springs with identical stiffness and it can swing in the horizontal plane in all directions. In this study, an automatic custom-made release system was used to initiate mechanical perturbations in four different directions: back (B), front (F), left (L), right (R) (Fadillioglu et al., 2022a). By convention, these directions indicate in which direction the platform was accelerated after release of the platform. In each trial, a perturbation in one of the four possible directions was applied in a randomized order. Participants stood on the platform on their dominant leg, which were determined based on self-reports. If the participants were not sure which leg was their dominant leg, it was determined by means of test trials on the Posturomed before the measurements (Ringhof & Stein, 2018). During single-leg stand, they kept their hands placed at the hips and their eyes focused on a target positioned at eye level and 4 m away from the center of the Posturomed (Figure 7.1).

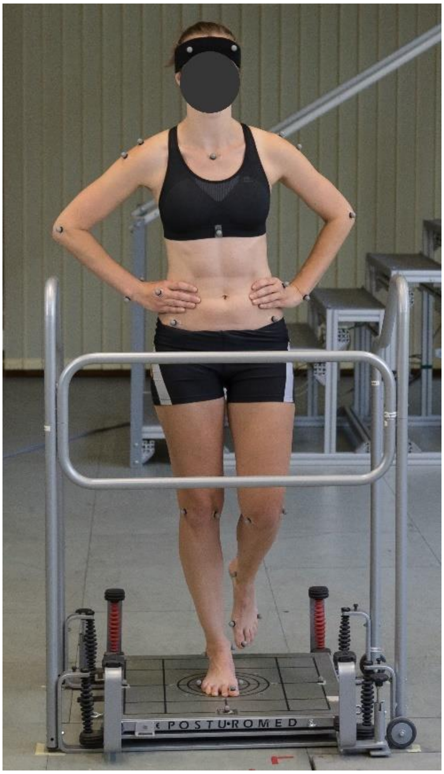

Figure 7.1: Participant during single-leg stand on the Posturomed oscillating platform.

7.3.2.2 Group assignment and masticatory system statuses

For familiarization, each participant performed two trials without and two trials with perturbation on the Posturomed. After that, a baseline measurement with perturbation and in habitual stomatognathic motor condition was conducted to determine the initial balance performance quantified by Lehr's damping ratio (DR) (Kiss, 2011a). Based on both balance performance and gender, each participant was assigned to one of three groups, such that both gender and the initial level of performance of the groups were balanced. The statistical examination by a one-way ANOVA revealed no baseline performance differences between the three groups ($p = 0.767$). Each group (JAW, TON and HAB) consisted of 16 participants and performed one of the stomatognathic motor conditions simultaneously with the balance task during the measurements (Table 5.1).

Table 7.1: Stomatognathic motor conditions of the three groups, JAW, TON and HAB.

JAW: instructed, controlled submaximal jaw clenching with a 75 N force - activity of the masticatory muscles during simultaneous occlusal loading
TON: instructed, controlled submaximal tongue pressing against the palate - stomatognathic muscle activity without occlusal loading
HAB: habitual stomatognathic behavior - jaw positioning without any instruction

The stomatognathic motor activity was recorded by an EMG system (detailed information in the “Data collection” section). To ensure that a force of 75 N was consistently applied, the participants in the JAW group trained just before data acquisition with a RehaBite® (Plastyle GmbH, Uttenreuth, Germany). This medical training device with liquid-filled plastic pads works based on hydrostatic principles, and can be used to control the applied force (Giannakopoulos, Rauer, et al., 2018). As the participants trained with the RehaBite®, masseter activity was monitored to determine the corresponding muscle activity level associated with a jaw clenching force of 75 N. The determined masseter activity level was around 5% maximum voluntary contraction (MVC) for all participants and was used to control if the submaximal jaw clenching condition was fulfilled.

The TON group similarly trained to apply a submaximal force with the tip of the tongue against the anterior hard palate corresponding to an EMG activity level of the suprahyoid muscles of the floor of the mouth of 5% MVC. Both groups trained for the stomatognathic motor task for five minutes. The HAB did not receive any training or instructions. During the measurements, the JAW group performed the jaw clenching task on an Aqualizer® intraoral splint (medium volume; Dentrade International, Cologne, Germany).

7.3.3 Data collection

A 3D motion capture system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK; 10 Vantage V8 and 6 Vero V2.2 cameras with a recording frequency of 200 Hz) was used to record the movements of the Posturomed platform and the participants. Four reflective markers were attached on the upper surface of the Posturomed platform. A further 42 reflective markers were attached to the participants' skin in accordance with the ALASKA modelling system (Advanced Lagrangian Solver in kinetic Analysis, Insys GmbH, Chemnitz, Germany; (Härtel & Hermsdorf, 2006)). Before data acquisition, 22 anthropometric measures were manually taken from each participant for the ALASKA modelling.

A wireless EMG system (Noraxon, Scottsdale, USA; recording frequency of 2000 Hz) was used to measure EMG activity of the masseter for JAW and HAB; and of the suprahyoid muscles of the floor of the mouth measured in the region of the digastricus venter anterior muscle for TON. As preparation, the skin over the corresponding muscles was carefully shaved, abraded and rinsed with alcohol. Bipolar Ag/AgCl surface electrodes (diameter 14 mm, center-to-center distance 20 mm; Noraxon Dual Electrodes, Noraxon, Scottsdale, USA) were positioned in accordance with the European Recommendations for Surface Electromyography (Hermens et al., 1999). Afterwards, MVC tests were performed.

For each trial, participants received standardized instruction about the task to be performed and were asked to compensate the perturbation as quickly as possible and to stabilize their body. Between each trial, participants had two minutes of rest to prevent fatigue. Measurements ended after completion of 12 successful balance task trials (i.e. three trials for each direction) each lasting 20 s after initiation of the perturbation. During the measurements, EMG activity of the masseter (for the JAW group) or the suprahyoid muscles of the floor of the mouth (for the TON group) was monitored and compared with the individually determined EMG activity level corresponding to 5% of MVC. Recordings were stopped and the trial was considered invalid if participants stopped performing their stomatognathic motor task (JAW and TON), had ground contact with the non-standing foot, changed the placement of their standing foot, released one of the hands from the hip or lost their balance. All data were recorded in Vicon Nexus 2.10; where the EMG system was connected via the Noraxon plug-in.

7.3.4 Data analysis

The collected data of 576 trials (48 participants x three valid trials x four directions) were exported from Vicon Nexus for further analysis in MATLAB R2020a (MathWorks; Natick, USA). For all data, the R and L directions were re-sorted as ipsilateral (I) and contralateral (C) according to the standing leg of the participants.

The marker data were filtered with a Butterworth low-pass filter (fourth-order; cut-off frequency 10 Hz); and the EMG data with a Butterworth band-pass filter (fourth-order; cut-off frequency 10 to 500 Hz). The EMG data were then rectified and smoothed by averaging with a sliding window of 30 ms and normalized to the MVC amplitudes (Hellmann et al., 2011a).

Based on Posturomed marker data, two critical time points were separately determined for each trial: (1) the start of the perturbation, and (2) the third highest amplitude of the Posturomed center in the direction of perturbation (Kiss, 2011a). The time span between (1) and (2) was assumed to be the phase in which the perturbation was maximally compensated, and the time frames after (2) were considered the dynamic steady-state phase of the movement. For all calculations, a time window of 12 s (Müller et al., 2004) was used which started at time point (2).

7.3.5 Spatial dynamics of CoM sway

To quantify the spatial dynamics of the CoM sway, the PL was calculated. The time series of CoM position was estimated by the subject-specific anthropometric 3D model referenced and explained below (see 7.3.7 Uncontrolled manifold approach). The point-by-point Euclidean norm of the vectors containing the 3D coordinates of the CoM was calculated to convert the three components in the x, y and z coordinates into a single value *k*, where *i* stands for the frame number (Eq. 7.1). PL was approximated by the sum of the distances between consecutive points of the time series *k* with a length of *n* (Prieto et al., 1996), where *n* equals the total number of frames in a 12 s interval (n = 2400; Eq. 7.2).

$$k_i = \sqrt{{x_i}^2 + {y_i}^2 + {z_i}^2};\ where\ \ i = 1,2,3,\ldots,n \tag{7.1}$$

$$PL = \sum_{i=1}^{n-1} |k_{i+1} - k_i| \tag{7.2}$$

7.3.6 Temporal dynamics of CoM sway

A detrended fluctuation analysis was performed to quantify the temporal dynamics of CoM sway. Firstly, an integrated time series was calculated by subtracting its mean from it (Eq. 7.3). Secondly, the data were divided into non-overlapping segments of length *m* and the linear approximation was estimated by a separate least square fit in each segment. Thirdly, average fluctuation of the time series around the trend was calculated as given in Eq. 7.4. The last two steps were repeated for all the considered m.

$$y(k) = \sum_{i=1}^{k}(k(i) - k_{avg}) \tag{7.3}$$

$$F(m) = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(y(k) - y_m(k))^2} \tag{7.4}$$

In general F(m) increases with the increasing m and a power law is expected where the scaling component α is a constant (Eq. 7.5). If $\alpha < 0.5$ or $1 < \alpha < 1.5$, the time series interpreted as anti-persistent, where a smaller α indicates a more anti-persistent behavior. If $0.5 < \alpha < 1$ or $1.5 < \alpha < 2$, the time series is persistent and the larger the α, the more persistent is the time series (Lin et al., 2008).

$$F(m) \propto m^{\alpha} \tag{7.5}$$

7.3.7 Uncontrolled Manifold approach

A UCM approach was applied to investigate if and how the co-variation of the joint movements led to the stabilization and control of the CoM. In accordance with the literature, the CoM and the joint angles were selected as PV and EVs, respectively (Freitas et al., 2006; Hagio et al., 2020; Hsu et al., 2013, 2017; Krishnamoorthy et al., 2005; Scholz et al., 2007). To obtain joint angles, an inverse kinematics calculation was performed using a modified version of the full-body Dynamicus (ALASKA) model (Härtel & Hermsdorf, 2006). A subject-specific anthropometric 3D model was used to estimate the CoM as the weighted sum of the body segments (Möhler et al., 2019).

The model was a modified version of the Hanavan model and had 50 degrees of freedom (Hanavan, 1964). Of the 36 subject-specific anthropometric measurements needed to calculate the CoM according to this model, 21 were taken manually and 15 were determined from the reflective markers. A constant density was assumed (Ackland et al., 1988) and the mass of each segment was estimated by volume integration. The whole-body CoM in

3D, r_{CoM} , was determined by calculating the weighted sum of the body segments using Eq. 7.6, where *N* is the total number of segments (*N* = 17; V_m the volume of the m^{th} segment; and r_m the center of gravity vector of the m^{th} segment.

$$r_{CoM} = \frac{1}{\sum_{i=1}^{N} V_m} * \sum_{m=1}^{N} r_m V_m \tag{7.6}$$

The CoM, as the PV for the UCM, was defined as a function of the joint angles as the EVs ($r_{CoM} = f(\theta_1, \theta_2, \dots, \theta_j)$, where j stands for the number of EVs). The mean joint configuration across each trial, θ^0, was calculated as an approximation of the desired configuration (Latash et al., 2007). The Jacobian matrix, $J(\theta^0)$, containing all first-order partial derivatives of the CoM coordinates with respect to the joint angles, was calculated at this reference joint configuration. Afterwards the null space of the matrix was computed as the linear estimate of the UCM (Eq. 7.7). The null space of the Jacobian matrix is the linear subspace of all joint angle combinations that does not affect the position of the CoM, and it is spanned by *j-d* number of basis vectors ε_i, where *j* and *d* are the number of dimensions of EVs and PV, respectively (Scholz & Schöner, 1999).

$$0 = J(\theta^0) \cdot \varepsilon_i \tag{7.7}$$

At each instant of n = 2400 trials (t = 12 s, recording frequency 200 Hz), the deviation from the mean joint configuration ($\theta - \theta^0$) was calculated (Hsu et al., 2013; Scholz et al., 2007) and subsequently resolved into their projection on the null space to decompose it into the parallel, $\theta_{\parallel}$, and orthogonal, $\theta_{\perp}$, components (Möhler et al., 2019; Scholz & Schöner, 1999) (Eq. 7.8-9).

$$\theta_{\parallel} = \sum_{i=1}^{j-d} \varepsilon_i^T (\theta - \theta^0)\, \varepsilon_i \tag{7.8}$$

$$\theta_{\perp} = (\theta - \theta^0) - \theta_{\parallel} \tag{7.9}$$

Finally, the amount of variability parallel to the UCM ($UCM_{\parallel}$, i.e. stabilizing PV) and orthogonal to the UCM ($UCM_{\perp}$, i.e. changing PV) were estimated (Scholz & Schöner, 1999) (Eq. 7.10-11). UCM_{Ratio}, the ratio of the two UCM components was calculated as suggested by (Papi et al., 2015) to obtain a symmetrical distribution (i.e. [-1 1]. The midpoint 0 is the threshold for “synergy” and therefore appropriate for statistical calculations (Eq. 7.12).

$$UCM_{\parallel} = \sqrt{\frac{1}{n \cdot (j-d)} \sum_{i=1}^{n} \theta_{\parallel i}^{2}} \tag{7.10}$$

$$UCM_{\perp} = \sqrt{\frac{1}{n \cdot d} \sum_{i=1}^{n} \theta_{\perp i}^{2}} \tag{7.11}$$

$$UCM_{Ratio} = \left(\frac{2 \cdot {UCM_{\parallel}}^{2}}{{UCM_{\parallel}}^{2} + {UCM_{\perp}}^{2}}\right) - 1 \tag{7.12}$$

The $UCM_{\parallel}$ component is a measure of the co-variation of EVs and therefore a measure for flexibility. A higher $UCM_{\parallel}$ indicates a higher variability on the level of the EVs that does not change the PV, and therefore a more flexible behavior of the control system, and vice versa. The $UCM_{\perp}$ component is a measure for control of the PV. The higher the $UCM_{\perp}$, the less controlled the PV, which in this study is the CoM. Lastly, UCM_{Ratio} indicates the stability of the PV by means of kinematic synergy of the EVs. A $UCM_{Ratio} > 0$ is interpreted as a synergy, whereas a $UCM_{Ratio} \leq 0$ indicates no synergy (Latash et al., 2007). In this study, UCM_{Ratio} and $UCM_{\perp}$ were used to quantify the stability and control of the CoM (i.e. the PV), respectively.

7.3.8 Statistics

Statistical analysis was performed with IBM SPSS Statistics 25.0 (IBM Corporation, Armonk, NY, USA). The PL of the CoM, DFA scaling component and three UCM parameters ($UCM_{\perp}$, UCM_{Ratio}) for three trials for each direction and for each subject were averaged. A Kolmogorov-Smirnov test was conducted to determine the normality of data distribution.

Each of the four directions of perturbation was analyzed separately because postural response may differ depending on the perturbation direction (Akay & Murray, 2021; C. Chen et al., 2014; Freyler et al., 2015; Kiss, 2011b; Nonnekes et al., 2013). For each of the four considered parameters and for each direction, a one-way ANOVA or a Kruskal-Wallis test was performed for the group comparisons depending on the normality of the distribution. The level of significance was set *a priori* to p < 0.05. Partial eta squared (η_p^2) or Cramer's V (ϕ_c) (small effect: η_p^2 < 0.06 or ϕ_c < 0.2; medium effect: 0.06 < η_p^2 < 0.14 or 0.2 < ϕ_c < 0.6;

large effect: η_p^2 > 0.14 or ϕ_c > 0.6; (Cohen, 1988; Richardson, 2011)) were calculated to estimate the effect sizes for normal and non-normal distribution of data, respectively.

7.4 Results

7.4.1 Sway of the center of mass

The operationalization of CoM sway in relation to the different stomatognathic motor conditions was analyzed by the PL of the 3D CoM trajectory (Table 7.2). The PL results did not show any significant changes between different stomatognathic motor conditions in the four perturbation directions. Although B, I and C had small effect sizes, F had a medium effect size (B: p = 0.429, η_p^2 = 0.037; F: p = 0.182, η_p^2 = 0.073; I: p = 0.461, η_p^2 = 0.034; C: p = 0.692, η_p^2 = 0.016).

7.4.2 Detrended fluctuation analysis

Temporal dynamics of CoM sway was analyzed with a DFA (Table 7.2). The scaling components did not differ significantly between different stomatognathic motor conditions in the four perturbation directions (B: p = 0.103, η_p^2 = 0.096; F: p = 0.724, η_p^2 = 0.014; I: p = 0.821, η_p^2 = 0.009; C: p = 0.689, η_p^2 = 0.016).

7.4.3 Uncontrolled manifold analysis

A UCM analysis was performed aiming at analyzing the co-variation of joint angles in relation with the control as well as the stability of the CoM. The $UCM_{\perp}$ and UCM_{Ratio} components were utilized to quantify the control and the stability of the CoM, respectively. The results are represented in Table 7.2.

For the $UCM_{\perp}$ component, the groups did not show any significant differences in any of the perturbation directions and all the effect sizes were small (B: p = 0.305, ϕ_c = 0.157; F: p = 0.466, η_p^2 = 0.033; I: p = 0.947, η_p^2 = 0.002; C: p = 0.514, η_p^2 = 0.029). This indicated the control of the CoM was not affected by the stomatognathic motor conditions (i.e. JAW, TON and HAB).

Table 7.2: The UCM, the path length (PL) and the DFA scaling exponent (α) results.

$UCM_{\perp}$ (rad²/dof)	JAW	TON	HAB	p	η_p^2 or ϕ_c
B	0.013 ± 0.012	0.012 ± 0.005	0.013 ± 0.006	0.305*	0.157*
F	0.011 ± 0.004	0.013 ± 0.006	0.013 ± 0.005	0.466	0.0333
I	0.017 ± 0.014	0.016 ± 0.009	0.016 ± 0.008	0.947	0.002
C	0.018 ± 0.011	0.015 ± 0.006	0.018 ± 0.006	0.514	0.029
UCM_{Ratio}	JAW	TON	HAB	p	η_p^2
B	0.209 ± 0.318	0.236 ± 0.202	0.1852 ± 0.2710	0.865	0.006
F	0.252 ± 0.319	0.220 ± 0.317	0.1022 ± 0.2482	0.333	0.048
I	0.249 ± 0.266	0.297 ± 0.165	0.2095 ± 0.2653	0.585	0.024
C	0.179 ± 0.433	0.237 ± 0.210	0.1634 ± 0.2664	0.788	0.011
PL (mm)	JAW	TON	HAB	p	η_p^2
B	325.2 ± 174.3	408.2 ± 277.5	329.4 ± 119.3	0.429	0.037
F	267.1 ± 112.1	381.4 ± 253.1	304.4 ± 124.3	0.182	0.073
I	369.2 ± 186.2	423.3 ± 219.6	344.7 ± 125.1	0.461	0.034
C	366.7 ± 154.8	428.8 ± 295.3	395.6 ± 117.3	0.692	0.016
α	JAW	TON	HAB	p	η_p^2
B	1.68 ± 0.12	1.74 ± 0.09	1.76 ± 0.11	0.103	0.096
F	1.73 ± 0.08	1.75 ± 0.09	1.73 ± 0.08	0.724	0.014
I	1.73 ± 0.08	1.72 ± 0.08	1.74 ± 0.09	0.821	0.009
C	1.72 ± 0.09	1.70 ± 0.10	1.71 ± 0.08	0.689	0.016

Regarding the UCM_{Ratio}, the groups did not differ significantly in any of the perturbation directions and all of the results showed small effect sizes (B: p = 0.805, η_p^2 = 0.006; F: p = 0.333, η_p^2 = 0.048; I: p = 0.585, η_p^2 = 0.024; C: p = 0.788, η_p^2 = 0.011). These results showed that the stability of the CoM was not affected by the stomatognathic motor conditions (i.e. JAW, TON and HAB).

7.5 Discussion

The aim of this study was to investigate the effects of different stomatognathic motor conditions on the sway, control and stability of the CoM during a dynamic steady-state balance task. The PL of the 3D CoM, a DFA and a UCM analyses were used to quantify the variables of interest. It was hypothesized that jaw clenching and tongue pressing decrease the total sway, increase the persistency of CoM fluctuations, increase both the control and stability of the CoM. Inclusion of the TON group would enable a differentiation between the specific effects of jaw clenching with occlusal load from the effects of stomatognathic motor activity in general, as well as from the dual-task effects. This could ultimately help to understand if the possible modulations of posture during jaw clenching occur basically due to a supra-postural task (Stoffregen et al., 2000) or stomatognathic activities in general; or if any additional functional interactions such as higher excitability of the human motor system (Boroojerdi et al., 2000), muscle co-contractions (Giannakopoulos, Schindler, et al., 2018) or H-reflex responses (Miyahara et al., 1996) may exist. None of the considered parameters showed significant group effects in any of the directions. Based on these results, it can be concluded that deliberate jaw clenching or tongue pressing do not have significant effects on the control or stability of the CoM compared to habitual stomatognathic motor conditions in the steady-state phase of the task. At least, the effects could not be quantified by the used parameters. In contrast to the previously-found effects of jaw clenching on dynamic reactive balance performance (Fadillioglu et al., 2022a), the findings in this study do not indicate any task-specific effects of stomatognathic motor activities on dynamic steady-state balance assessed by an oscillating platform. Because of the task-specificity of balance (Giboin et al., 2015; Kümmel et al., 2016; Ringhof & Stein, 2018), further research investigating the effects of stomatognathic motor activities on dynamic steady-state balance with different movement tasks are needed. To the best of our knowledge, the present study is the first to investigate the effects of stomatognathic motor activity on dynamic steady-state balance on an oscillating platform.

7.5.1 Quantification of CoM sway

The PL of the 3D CoM position was calculated to quantify the distance covered by the CoM during the trials. The results in this study revealed no significant differences between the three groups for any of the directions. Nevertheless, the effect sizes for the direction F were medium (p = 0.182; η_p^2 = 0.073), where the JAW group had a slightly smaller PL compared to TON and HAB, indicating a higher dynamic steady-state stability. It should be noted that significant performance increases and decreased anatomical region speeds were seen in the F direction during the early reactive phase of the task (Fadillioglu et al., 2022a). Although a medium effect size does not have a high statistical power, jaw clenching may have effects on the steady-state stability; but these were not high enough to be detected with the chosen methods.

The temporal dynamics of CoM sway was analyzed by a DFA, which did not show any significant differences between groups. Overall, the scaling exponent α was larger than 1.5 for all directions and all groups, indicating a Brownian noise (McGrath, 2016). These results were slightly higher but similar to those of Liang et al. (2017), which considered the CoM instead of center of pressure for DFA (Blázquez et al., 2010; Lin et al., 2008; Munafo et al., 2016) as in the present study. On the other hand, even though DFA has become a predominant method for fractal analysis, it may not provide useful results for short time series (McGrath, 2016).

7.5.2 Analysis of control and stability of the CoM by a UCM approach

A UCM approach was applied to investigate the co-variated movement of joints in relation to the CoM position as the PV (Freitas et al., 2006; Hagio et al., 2020; Hsu et al., 2013, 2017; Krishnamoorthy et al., 2005; Scholz et al., 2007) under different stomatognathic motor conditions. In this study, the $UCM_{\perp}$ and the UCM_{Ratio} were directly included in the analysis, whereas the $UCM_{\parallel}$ was only indirectly considered within the UCM_{Ratio}. The findings indicate that jaw clenching or tongue pressing do not lead to any effects that are quantifiable with the UCM approach.

The UCM_{Ratio} component was used to investigate the stabilization of the CoM through co-varied movements of the joint angles. The statistical analysis revealed that the three groups did not differ in UCM_{Ratio}. This showed that jaw clenching or tongue pressing did not lead to a more stable CoM compared to habitual stomatognathic motor conditions in the steady-state phase of the task. Therefore, it contradicted our first hypothesis regarding the stability of the CoM.

The $UCM_{\perp}$ component was used to quantify the control of the CoM. The results showed that the groups did not differ in terms of control of the CoM, which suggested that jaw clenching or tongue pressing did not lead to a better control compared to habitual conditions. Based on this result, the second hypothesis was rejected.

A UCM analysis was performed in the present study and a subject-specific anthropometric 3D model was used to estimate the CoM (Möhler et al., 2019). Therefore, the model covered all three movement planes and considered not only the lower body but also the upper body, which plays an important role in the movement of the CoM due to its high mass.

7.5.3 Effects of masticatory system on dynamic stability

As already described in the introduction, there are some phenomena described in the literature that support the assumption of a close functional integration of the masticatory system in the human motor control processes (Boroojerdi et al., 2000; Bracha, Bracha, et al., 2005; Bracha, Ralston, et al., 2005; Julià-Sánchez et al., 2020; Miyahara et al., 1996). This could be because jaw movements are proportionally driven by anterior neck muscles, which inevitably requires co-contractions of the lateral and posterior neck muscles (Giannakopoulos, Schindler, et al., 2018). The resulting movements of the head must in turn be matched centrally with the further proprioceptive input of postural control. Therefore, the integration of the stomatognathic system into postural control is not a phenomenon, but a basic requirement.

Jaw clenching during activities that involve the lower and upper limbs may enhance neuromotor stimulation by means of the H-reflex, and therefore increase the excitability of the motor system (de Souza et al., 2021). Furthermore, high activity was observed in the frontal, parietal, and temporal cortices and cerebellum during hand grip combined with jaw clenching compared to without jaw clenching (Kawakubo et al., 2014). In addition, there are also studies revealing that not only stomatognathic activity but also the use of occlusal splints (Battaglia et al., 2018) or mouthguards (Dias et al., 2022) influence the strength in the muscles of the other body parts. These findings indicate that there is a close relationship between the masticatory system and muscle strength or physical exertion. Although it is hard to verify the underlying mechanisms experimentally, based on these findings it was hypothesized that jaw clenching may lead to better dynamic steady-state stability also under dynamic conditions. However, the results in this study did not support this hypothesis.

7.5.4 Consideration of methodical aspects

Based on their gender and baseline performance, the participants were allocated into one of the three groups (JAW, TON and HAB). The statistical examination by ANOVA revealed that there were no baseline performance differences between the three groups (p =

0.767). The purpose of building three groups with different stomatognathic motor conditions, instead of making all participants perform all the tasks, was due to three main reasons. Firstly, "habitual" in this study meant that no instruction was given regarding the stomatognathic motor activity. Therefore, an unconscious, natural behavioral pattern of the masticatory system was ensured. An instructed “habitual” would not be physiologically possible, because an "instructed" behavioral pattern cannot lead to an unconsciously performed behavior. Secondly, possible carry over effects between different stomatognathic motor tasks were avoided. After jaw clenching or tongue pressing, there could be sustained physiological effects such as an increased excitability of the motor system. Thirdly, fatigue effects were avoided. If all tasks were performed for each of the four directions separately, 36 valid trials would be needed. Considering the invalid trials as well, the total number performed would be too high.

In this study, the Posturomed, an oscillating platform, was used to assess dynamic balance performance. The platform was randomly perturbed in one of the four different directions. The perturbation directions were analyzed independently following the suggestions of Freyler et al. (2015), because muscle spindles provide different information depending on the direction as well the velocity of perturbations (Akay & Murray, 2021). In addition to this, the direction of surface translation is an important factor for the sensation, processing and output of the postural responses (Freyler et al., 2015; Nonnekes et al., 2013). Although it was suggested that the perturbation direction may not matter during the steady-state phase of the balancing task on an oscillating platform (Giboin et al., 2015), in this study the directions were analyzed separately since the research question was to further investigate the positive effects of jaw clenching, which was found only in one direction (Fadillioglu et al., 2022a).

The focus was put on the CoM in this study because it is suggested to be the controlled variable in postural studies (Kilby et al., 2015; Nicolai & Audiffren, 2019; Richmond et al., 2021; Winter et al., 1998). Also, in studies assessing dynamic stability by means of an oscillating platform, the CoM was considered as an important variable (Pfusterschmied, Buchecker, et al., 2013; Pohl et al., 2020). Even if it is widely chosen for postural studies and others from the field of motor control (Domkin et al., 2005; Maldonado et al., 2018; Möhler et al., 2019; Qu, 2012; Reisman et al., 2002; Scholz et al., 2000, 2001; Tseng et al., 2002; Verrel et al., 2010), it does not prove that it is the single right one. Another possible PV could be the distance between the CoM and the center of the platform.

7.5.5 Limitations

All the participants in this study were physically active adults. The homogeneity of this group helped to minimize altered postural control mechanisms due to, for example, age (M. Henry & Baudry, 2019) or neurological disorders (Delafontaine et al., 2020). Nevertheless, it should be noted that the findings cannot be directly transferred to other groups (e.g., elders or people with neurological disorders).

The stabilization of a moving platform and the stabilization of the body on a rigid surface are different balance tasks (Alizadehsaravi et al., 2020). Therefore, it should be added that the findings in this study may not be valid for balance tasks on stationary ground or for other dynamic tasks (Giboin et al., 2015; Kümmel et al., 2016; Ringhof & Stein, 2018).

It is possible that the UCM approach and the model used in the study were not sensitive enough to capture the possible effects due the different stomatognathic motor activities. Therefore, further research investigating the effects of stomatognathic motor activities on dynamic steady-state balance with other models could be useful. Additionally, further analysis by use of muscle synergies (D'Avella et al., 2003) or co-contractions (Hellmann et al., 2015) may reveal effects on the level of muscles, which were not visible on the level of kinematics.

7.6 Conclusion and Outlook

To the best of our knowledge, this study investigates for the first time the effects of different stomatognathic motor conditions (jaw clenching, tongue pressing and habitual condition) on dynamic steady-state balance. The aim was to analyze the effects particularly on the sway, control and stability of the CoM during a dynamic steady-state task (standing one-legged on an oscillating platform). The results revealed that deliberate jaw clenching or tongue pressing do not seem to affect the sway, the control or the stability of the CoM during a dynamic balance task on an oscillating platform. Due to the task-specificity of balance, further research investigating the effects of stomatognathic motor activities on dynamic steady-state balance with different movement tasks is needed. In addition, further analysis by use of muscle synergies or co-contractions may reveal effects on the level of muscles, which were not visible on the level of kinematics. This study can contribute to the understanding of postural control mechanisms, particularly in relation to stomatognathic motor activities

8 Study V – Modulation of Postural Control – Dynamic Steady-State Balance

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8.1 Abstract

The effects of jaw clenching on balance has been shown under static steady-state conditions but the effects on dynamic steady-state balance have not yet been investigated. On this basis, the research questions were: 1) if jaw clenching improves dynamic steady-state balance; 2) if the effects persist when the jaw clenching task loses its novelty and the increased attention associated with it; 3) if the improved dynamic steady-state balance performance is associated with decreased muscle activity. A total of 48 physically active healthy adults were assigned to three groups differing in intervention (Jaw clenching and balance training (JBT), only balance training (OBT) or the no-training control group (CON)) and attending two measurement points separated by two weeks. A stabilometer was used to assess the dynamic steady-state balance performance in a jaw clenching and non-clenching condition. Dynamic steady-state balance performance was measured by the time at equilibrium (TAE). The activities of tibialis anterior (TA), gastrocnemius medialis (GM), rectus femoris (RF), biceps femoris (BF) and masseter (MA) muscles were recorded by a wireless EMG system. Integrated EMG (iEMG) was calculated to quantify the muscle activities. All groups had better dynamic steady-state balance performance in the jaw clenching condition than non-clenching at T1, and the positive effects persisted at T2 even though the jaw clenching task lost its novelty and attention associated with it after balance training with simultaneous jaw clenching. Independent of the intervention, all groups had better dynamic steady-state balance performances at T2. Moreover, reductions in muscle activities were observed at T2 parallel to the dynamic steady-state balance performance improvement. Previous studies showed that jaw clenching alters balance

during upright standing, predictable perturbations when standing on the ground and unpredictable perturbations when standing on an oscillating platform. This study complemented the previous findings by showing positive effects of jaw clenching on dynamic steady-state balance performance.

8.2 Introduction

The postural control system regulates the body's position with respect to the environment for the dual purposes of balance and orientation (Macpherson & Horak, 2013). Good balance is crucial for daily activities and is associated with decreased risk of falls (Rubenstein, 2006) and injuries (Hrysomallis, 2007). Therefore, the methods to improve postural control, such as balance training (Giboin et al., 2019), are highly appreciated. However, balance is not a general ability but task-specific (Giboin et al., 2015). Balance can generally be classified as static steady-state, dynamic steady-state, dynamic reactive and dynamic proactive based on the performed activity (Lesinski et al., 2015b). Static steady-state balance basically comprises unperturbed conditions, such as during quiet upright standing, whereas dynamic steady-state balance involves the maintenance of a steady position while moving (e.g., walking). Dynamic reactive balance can be defined as the compensation of an unpredicted postural perturbation to maintain the balance. In case of proactive balance, a predicted perturbation is anticipated and compensated before balance is disturbed (Macpherson & Horak, 2013; Shumway-Cook & Woollacott, 2017). Good balance in one of these sub-categories does not necessarily mean good balance in the others due to the task specificity of balance (Shumway-Cook & Woollacott, 2017). Against this background, the effects of balance must be investigated in individual sub-categories.

Postural control can be influenced by many factors including the status and activity of the stomatognathic system. There is a growing body of literature showing the associations between postural activities under static steady-state conditions and stomatognathic motor activities in the form of jaw clenching in different jaw relationships (e.g., maximum intercuspation or different occlusal appliances) (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015). Particularly regarding jaw clenching, a lower sway of body in the anterior– posterior direction (Hellmann et al., 2011a; Ringhof, Leibold, et al., 2015), a lower variability in muscular co-contraction patterns (Hellmann et al., 2015) and lower sway of trunk and head during upright standing (Ringhof, Stein, et al., 2015) were previously reported. The effects of jaw clenching on dynamic and proactive balance (Fadillioglu et al., 2022a; Tomita et al., 2021) were also shown. However, the effects of jaw clenching on dynamic steady-state balance are not well known (Fadillioglu et al., 2022b).

Despite the growing evidence for a relationship between the stomatognathic system and postural activities, the underlying mechanisms are not fully understood. Several studies (e.g., Boroojerdi et al., 2000; Miyahara et al., 1996) suggested that jaw clenching may result in increased motor excitability similar to the Jendrassik maneuver (Gregory et al., 2001), or an increased muscle force in association with the H-reflex mechanism (de Souza et al., 2021). Also, the co-contraction pattern of the jaw and neck muscles may help to improve postural control by contributing to a more stable head or gaze position (Gangloff et al., 2000). Furthermore, neuronal links of the trigeminal nerve to the rest of the nervous system were shown in animal models (Ruggiero et al., 1981). Another possible explanation might be that the instruction of jaw clenching during the simultaneous performance of a balancing task might create a dual-task scenario. In this case, the attention increases due to the secondary task, and consequently automatization of postural control is enhanced (Wachholz et al., 2020). Based on these findings, it may be hypothesized that simultaneous execution of the jaw clenching task improves balance performance due to its novelty and increased requirement of attention, but not specifically due to neurophysiological effects.

Previous studies showed various effects of jaw clenching during upright standing (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015), during predictable perturbations applied when standing on the ground (Tomita et al., 2021) and during unpredictable perturbations when standing on an oscillating platform (Fadillioglu et al., 2022a). However, the effects of jaw clenching during a dynamic steady-state balance task have not been fully investigated. In this study, this research gap was addressed. Using two measurement times (T1 and T2) two weeks apart, it was evaluated whether the stabilizing effects of jaw clenching persist at T2, despite the diminished novelty and competing influence of a secondary task (and therefore decreased attention). It was hypothesized that (1) jaw clenching improves dynamic steady-state balance at T1; (2) the effects persist at T2; and (3) better dynamic steady-state balance performance is associated with decreased muscle activity due to movement efficiency (Brueckner et al., 2019).

8.3 Methods

8.3.1 Participants

An *a priori* power analysis was conducted based on a study analyzing the effects of jaw clenching on postural stability during upright standing (Ringhof, Stein, et al., 2015). That analysis revealed that 16 participants per group would be enough to reach sufficient power (>0.8). On this basis, 48 healthy adults (21 female, 27 male; age: 22.9 ± 2.5 years; height: 1.74 ± 0.09 m; body mass: 70.0 ± 12.2 kg) voluntarily participated after giving written informed consent. They were physically active (active 4.2 ± 1.2 days/week and 368 ± 153 min/week), naive to the stabilometer task and had no muscular or neurological diseases. They had no signs and symptoms of temporomandibular disorders (assessed by means of the research diagnostic criteria for temporomandibular disorders (Dworkin & LeResche, 1992)) and presented with full dentition (except for 3rd molars) in neutral occlusion. The recruitment period for this study was between 13.09.2021-27.07.2022. The study was approved by the Ethics Committee of the Karlsruhe Institute of Technology.

8.3.2 Instrumentation

Dynamic steady-state balance was assessed using a stabilometer (Stability Platform, Model 16030, Lafayette Instrument Company, Lafayette, IN, USA) containing a 65×107 cm wooden platform with a maximum deviation of ± 15° (Figure 8.1a-b). EMG data of the tibialis anterior (TA), gastrocnemius medialis (GM), rectus femoris (RF), biceps femoris (BF) and masseter (MA) of the right side were recorded by a wireless EMG system (Noraxon, Scottsdale, USA; 2000 Hz). As preparation, the skin over the muscles was carefully shaved, abraded, and rinsed with alcohol. Bipolar Ag/AgCl surface electrodes (diameter 14 mm, center-to-center distance 20 mm; Noraxon Dual Electrodes, Noraxon, Scottsdale, USA) were positioned in accordance with the European Recommendations for Surface EMG (Hermens et al., 1999). The positions of the EMG electrodes were marked with temporary tattoo ink (MyJagua, Greven, Germany) at T1 to allow identical positioning at T2.

8.3.3 Protocol

The experimental protocol is illustrated in Fig 8.1c. First, the participants were familiarized to the stabilometer by standing on it for 1 min with rubber bands under it (the easier form of the task), then for 1 min without the rubber bands (the task to be performed during the measurements). Afterwards, a baseline measurement of 30 s was performed to determine the initial dynamic steady-state balance performance operationalized by the time at equilibrium (TAE; for details see the "Data analysis" section). Both baseline measurement result and gender were considered to assign the participants to one of three groups: jaw clenching and balance training (JBT), only balance training (OBT) or the no-training control group (CON). Statistical examination by one-way ANOVA revealed no baseline performance differences between the three groups (p = 0.982). All groups had 7 female and 9 male participants.

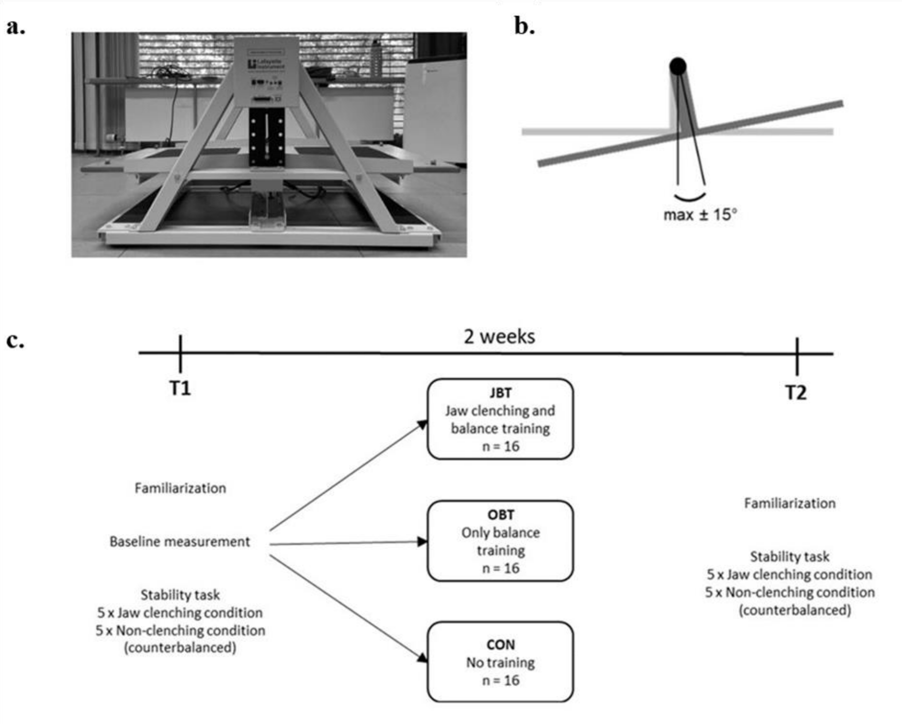

Figure 8.1: a. Stabilometer. b. Degrees of freedom and maximum deviation of the platform. c. Experimental protocol.

After warming up on a treadmill (h/p/cosmos Saturn, Nussdorf-Traunstein, Germany) for 5 min at 6 km/h, maximum voluntary contraction (MVC) tests were performed for each muscle. Just before the measurements, each participant trained with a RehaBite® (Plastyle GmbH, Uttenreuth, Germany) to become familiar with applying a submaximal force of 75 N (Hellmann et al., 2011a). The EMG data of MA were monitored during training to determine the corresponding muscle activity for later use as reference during the measurements (Fadillioglu et al., 2022a, 2022b). During the subsequent balancing task, participants clenched on an Aqualizer® intraoral splint (medium volume; Dentrade International, Cologne, Germany).

Regarding the balance task, participants were asked to keep the stabilometer platform in the horizontal position as long as possible and to focus on a target positioned at eye level and 3 m away from the center of the platform. For the jaw clenching trials, participants were asked to simultaneously clench their jaws. Five valid trials, each 30 s, were collected for each condition (clenching/non-clenching). There was a break of 30 s between each trial to avoid fatigue. The order of clenching conditions was counterbalanced within the groups and each participant was randomly assigned to an order. At T2, the same protocol as during T1 was executed except for the baseline measurement.

8.3.4 Intervention

Between T1 and T2, the participants of JBT and OBT followed a two-week training program comprising six training sessions at least two days apart from each other, whereas CON did not train. Each training session was performed in the BioMotion Center under the supervision of experienced staff and lasted about 15 min. As in the measurements, participants were asked to keep the platform in the horizontal position as long as possible. In total, 10 trials (2 sets of 5 trials) of 30 s were performed in each training session. There was a break of 30 s between each trial and 2 min between each set. The participants of JBT trained in the jaw clenching condition and OBT in the non-clenching condition. In each training session, JBT additionally trained with the Rehabite® for five minutes before balance training to get used to the jaw clenching task.

8.3.5 Data analysis

All data were recorded in Vicon Nexus 2.12 (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK) and exported for further processing in MATLAB R2022a (MathWorks, Natick, USA). The analog output signal of the platform was filtered with a Butterworth low-pass filter (fourth-order; cut-off frequency 10 Hz); and EMG data with a Butterworth band-pass filter (fourth-order; cut-off frequency 10-500 Hz). After filtering, EMG data were rectified and smoothed by averaging with a sliding window of 30 ms and finally normalized to the MVC references (Hellmann et al., 2011a). For each trial, time at equilibrium (TAE, ± 3° deviation from the horizontal position (Brueckner et al., 2019; Kiss, Brueckner, & Muehlbauer., 2018) for at least 500 ms (Giboin et al., 2015)) as well as time normalized iEMG for each muscle were calculated. A higher TAE was considered as better dynamic steady-state balance performance.

8.3.6 Statistics

Statistical analysis was done with IBM SPSS Statistics 29.0 (IBM Corporation, Armonk, NY, USA). Kolmogorov-Smirnov tests were performed to determine the normality of data distribution. For each measurement time and condition, the trial with the highest TAE was used for statistical tests.

For TAE at T1, a paired t-test was performed to analyze the effects of jaw clenching on dynamic steady-state balance performance (Hypothesis 1). Additionally, for each dependent parameter (i.e. TAE and iEMG), a three-factorial mixed ANOVA (3 groups x 2 clenching conditions x 2 measurement times) was conducted to test the remaining hypotheses. *Post-hoc* t-tests for pairwise group comparisons were run with Bonferroni-Holm corrections in the case of interaction effects. The correlation between the changes in dynamic steady-state balance performance (i.e. ΔTAE as TAE(T2)-TAE(T1)) and muscle activities (i.e. ΔiEMG as iEMG(T1)-iEMG(T2)) was quantified by Spearman correlation tests. By convention, a positive ΔTAE indicated an increased TAE at T2, whereas a positive ΔiEMG indicated a decreased iEMG at T2. The differences were normalized to the values at T1. The level of significance was set *a priori* to $p < 0.05$. Cohen's d and partial eta squared (η^2_p) were calculated to estimate effect sizes (small $\eta^2_p < 0.06$; medium: $0.06 < \eta^2_p < 0.14$; large: $\eta^2_p > 0.14$) (Cohen, 1988).

8.4 Results

The activity of MA was 7.9 ± 6.00% of MVC at T1 and 7.5 ± 5.4% of MVC at T2 for the jaw clenching condition, and for the non-clenching condition it was 0.4 ± 0.2% of MVC and 0.3 ± 0.2% of MVC at T1 and T2, respectively. This indicated that the participants performed the clenching tasks successfully.

The descriptive data of the TAE can be found in Appendix S3 Table1. The TAE results at T1 are presented in Fig 8.2. The TAE was significantly higher in the jaw clenching condition than the non-clenching condition at T1 with high effect sizes ($p = 0.006$, $d = 3.95$). This showed that all participants had a better dynamic steady-state balance performance in jaw clenching condition than the non-biting condition at T1, which was in line with the hypothesis 1.

The balance and jaw clenching training effects are depicted in Fig 8.3. The ANOVA results revealed statistically significant effects for the factor time ($p < 0.001$, $\eta^2_p = 0.616$) and the factor clenching condition ($p = 0.008$, $\eta^2_p = 0.146$) with high effect sizes. Although there were no significant interaction effects between the factors time and group, the effect size was medium ($p = 0.174$, $\eta^2_p = 0.075$). There were no significant differences between the groups over two clenching conditions, but the effects sizes were high (OBT vs. CON: $p = 0.207$, $d = 5.48$; JBT vs. OBT: $p = 0.356$, $d = 3.66$, JBT vs. CON: $p = 0.214$, $d = 5.50$). These results indicated that the effects of jaw-clenching on dynamic steady-state balance performance persisted at T2, which supported the hypothesis 2.

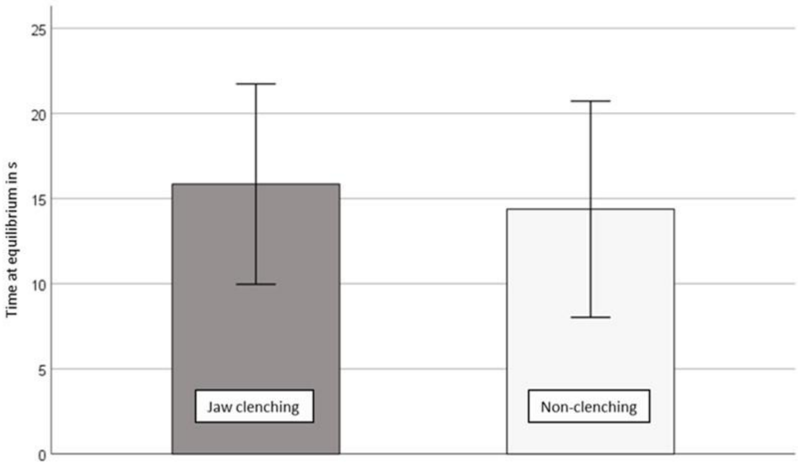

Figure 8.2: Time at equilibrium for two clenching conditions at T1.

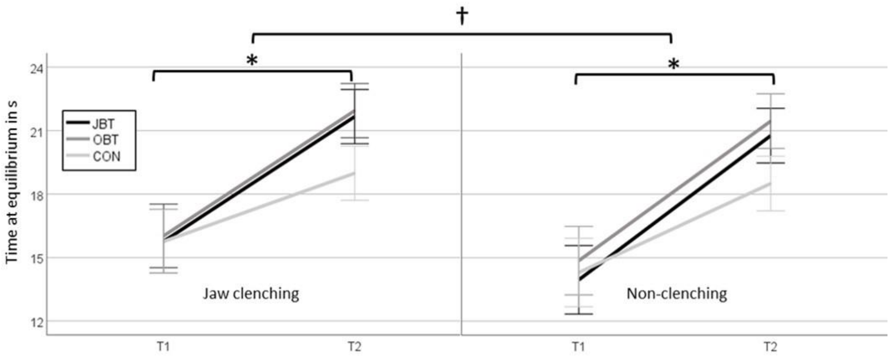

Figure 8.3: Time at equilibrium for the three groups at two measurement times. Significant differences for the factor time are indicated with * and for the factor clenching condition with †.

The time normalized iEMGs are represented in Fig 8.4 and the descriptive data can be found in S3 Table. The ANOVA results showed that all muscle activity was significantly decreased at T2 with high effect sizes (TA: $p < 0.001$, $\eta^2_p = 0.321$; GM: $p < 0.001$, $\eta^2_p = 0.289$; RF: $p < 0.001$, $\eta^2_p = 0.327$; and BF: $p < 0.001$, $\eta^2_p = 0.425$). Further, GM showed significant interaction effects between the factors time and clenching with a medium effect size (GM: $p = 0.034$, $\eta^2_p = 0.097$). These finding partly supported the hypothesis 3, since at T2 all the muscle activities decreased parallel to the dynamic steady-state balance performance improvement. However, in case of jaw clenching condition there was not any decrease in muscle activities although the dynamic steady-state balance performance was better.

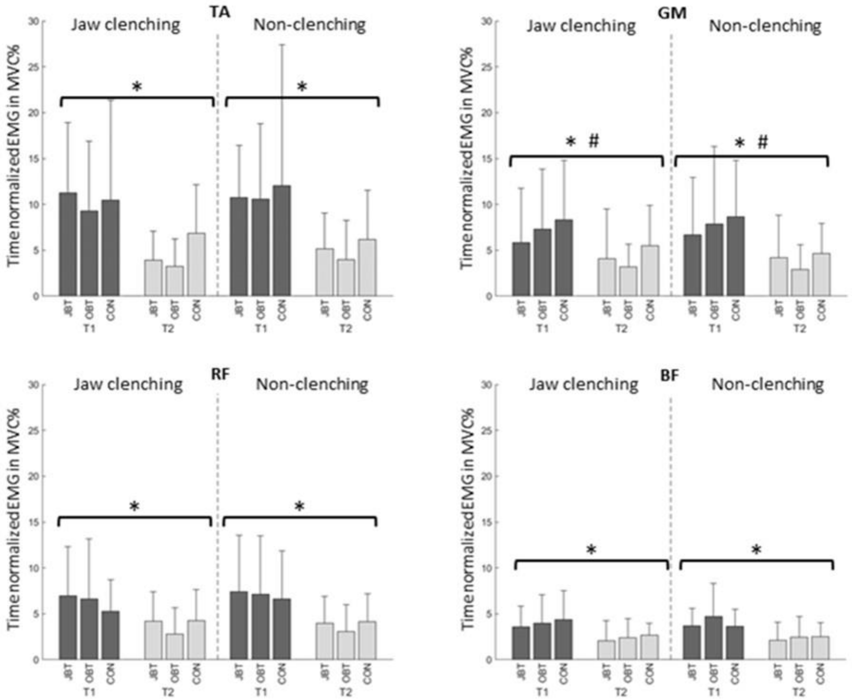

Figure 8.4: Time normalized iEMGs of four muscles: tibialis anterior (TA), gastrocnemius medialis (GM), rectus femoris (RF) and biceps femoris (BF). JBT= jaw clenching and balance training, OBT= only balance training and CON = no-training control group. Significant differences for the factor time are indicated with * and interaction effects between the factors time and clenching condition with #.

The TAE increases and iEMG decreases between two measurement points are represented as the medians and 25th-75th percentiles in Table 1 (Sainani, 2012). The correlations between the increases in TAE and the decreases in iEMG for all muscles are also shown in Table 1. The results showed that the dynamic steady-state balance performance improvements significantly correlated with the decreases in RF activity with a moderate correlation coefficient. The rest of the muscles did not show any significant correlations.

Table 8.1: Time at equilibrium (TAE) increases and iEMG decreases of tibialis anterior (TA), gastrocnemius medialis (GM), rectus femoris (RF) and biceps femoris (BF) between T1 and T2, together with their correlations. The results of the clenching and non-clenching conditions were averaged for both T1 and T2. Significant changes are shown in bold.

		Median	25^{th}-75^{th} percentile	Correlation with TAE	
				p	rho
TAE increase in %		36.4	[12.1 84.1]	-	-
iEMG decrease in %	**TA**	49.8	[29.8 76.6]	0.088	0.249
	GM	47.0	[23.0 65.2]	0.054	0.280
	RF	44.9	[14.3 59.5]	**0.011**	**0.366**
	BF	41.1	[9.1 59.0]	0.222	0.179

8.5 Discussion

This study investigated the effects of jaw clenching on dynamic steady-state balance task performance and investigated if the stabilizing effects of jaw clenching persist when the novelty of the task and the focused attention associated with it diminish. Further, activity of the selected task-relevant muscles was analyzed to better understand improvements in dynamic steady-state balance performance.

8.5.1 Persistence of jaw clenching effects

The results showed that dynamic steady-state balance performance was better in the jaw clenching condition compared with the non-clenching condition at both T1 and T2, which was consistent with previously-shown effects during static steady-state balance (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015). As the effects persist at T2, it can be suggested that the performance improvements are related specifically to the jaw clenching task, but not to the novelty of the secondary task and the accompanying automatization of the balance task. Various studies have shown that jaw clenching alters postural control during upright standing (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015), predictable perturbations, standing on the ground (Tomita et al., 2021) and during unpredictable perturbations applied when standing on an oscillating platform (Fadillioglu et al., 2022a). This study complemented the previous findings by showing positive effects of jaw clenching on dynamic steady-state balance performance.

8.5.2 No effects of balance training

In previous studies, training improved balance in a task-specific way (Giboin et al., 2019), reduced the incidence of falls (Sherrington et al., 2020) and enhanced motor performance (Gruber & Gollhofer, 2004). The current three-armed study design aimed to investigate the effects of simultaneous jaw clenching during balance training. Pairwise comparisons of the groups provide information on (1) if balance training alone improved the dynamic steady-state balance performance more than the no training condition (OBT vs. CON), and (2) if simultaneous jaw clenching during balance training altered the balance training effects (JBT vs. OBT) which can be explained by the automatization of the dual-task. All of the groups improved at T2 independent of their training situation. Interestingly, no significant interaction effects between the factors time and group were detected. This indicated that all groups improved their dynamic steady-state balance performance with no significant group differences. However, it should be noted that there was a medium interaction effect for TAE. Further, the *post-hoc* pairwise comparisons at T2 showed high effect sizes. The dynamic steady-state balance performance improvement, as the difference of TAE between T1 and T2 over two clenching conditions, were lower in CON by more than 2 s compared with the other two groups (JBT = 6.4 s, OBT = 6.3 s and CON = 3.7 s). Nevertheless, none of the differences reached the level of significance. Ultimately, the learning effects of the balance task were seemingly higher than the balance training effect, therefore the former outweighed the latter in terms of significance level. This finding is interesting since previous studies showed that dynamic steady-state balance performance improves after balance training comprising the same task used for testing (e.g., Giboin et al., 2015). On the other hand, learning effects within a measurement session were also reported in previous studies in which the stabiliometer was used to quantify the dynamic steady-state balance performance (Brueckner et al., 2019; Steiner et al., 2016). In this study, high learning effects of the balance task in the initial phase may have masked the effects of the balance training. For future studies, it is advisable to take more care to minimize possible learning effects when designing the study.

8.5.3 Limited effects of jaw clenching on muscle activity

The iEMG results revealed that all muscle activity decreased at T2. Considering that dynamic steady-state balance performance was better at T2, it can be suggested that better performance is associated with decreased muscle activities. However, the dynamic steady-state balance performance improvements and the muscle activity reductions from T1 to T2 correlated significantly only for one of the analyzed muscles, that is RF, with a moderate correlation coefficient. The reason for the non-significant correlations may be the linear approach used both for the calculation of the changes between the two measurement sessions and for the correlations. For example, in a previous study comparing the muscle activation during back squats with different loads showed that the correlation between the changes in the loads and the muscle activations are not linear (van den Tillaar et al., 2019). Based on this finding, it can be suggested that the non-linear approaches for the correlation between the dynamic steady-state balance performance improvements and the iEMG reductions might reveal significant and stronger correlations. Nevertheless, all of the muscles showed reduced activities at T2 parallel to the dynamic steady-state balance performance improvement. These findings are in line with previous studies (e.g., Brueckner et al., 2019) reporting practice-related reductions in muscle activations, which could relate to improved movement efficiency. On the other hand, the iEMG results in this study did not show any decrease in the jaw clenching condition, although the dynamic steady-state balance performance in the jaw clenching condition was significantly better than in the non-clenching. Further, the activity of GM decreased less at T2 in the jaw clenching condition compared with the non-clenching condition. Based on these findings, it can be suggested that dynamic steady-state balance performance improvement due to jaw clenching was not associated solely with movement efficiency, but could be explained by other mechanisms that are currently undiscovered.

8.5.4 Limitations

Certain limitations of this study should be considered (1) since the participants were physically active adults, the results are not necessarily valid for other groups. (2) The best trial was taken instead of the average of five trials, since previous studies reported that the participants improved their dynamic steady- state balance performances on the stabilometer during trials on the first measurement day (Brueckner et al., 2019; Steiner et al., 2016). Taking the best trials aimed to eliminate the additional effects due to different learning curves at T1 and T2. (3) Significant time effects were found even for the CON group, who did not train between two measurement times. These high learning effects may have outweighed the other effects. (4) Considering the task-specific characteristics of balance (Giboin et al., 2015), it is important to add that the results are not generalizable to other static or dynamic balance tasks.

8.6 Conclusion and Outlook

This study investigated the effects of jaw clenching on dynamic steady-state balance performance across two measurement times separated by two weeks. The findings indicated that jaw clenching was associated with a better dynamic steady-state balance performance and the effects persisted even when the jaw clenching task lost its novelty and competing influence. Independent of the intervention, all groups had better dynamic steady-state balance performances at T2, which indicated high learning effects of the dynamic steady-state balance task. Moreover, learning-related reductions in muscle activity were observed at T2.

9 General Discussion

Several studies reported that stomatognatic motor activities in the form of chewing as well as jaw clenching may affect postural control under static conditions (e.g., Hellmann et al., 2011a, 2015; Kushiro & Goto, 2011; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015). This entails, in particular, reduced anterior-posterior body sway (Hellmann et al., 2011a), reduced variability of muscular co-contraction patterns of posture-relevant muscles of the lower extremities, and reduced trunk and head sway in response to controlled stomatognatic motor activities (Hellmann et al., 2015). These neuromechnical effects can be interpreted as stabilizing effects concerning the body sway. However, good balance during a balance task does not necessarily mean good balance in the others due to the task-specific characteristics of balance (Giboin et al., 2015; Ringhof & Stein, 2018; Shumway-Cook & Woollacott, 2017).

In contrast to balance in more static conditions (e.g., sitting or standing), the influence of stomatognathic motor activities in dynamic situations (e.g., standing on an oscillating platform with perturbations) has not yet been thoroughly studied. In this thesis, this research gap was addressed. Furthermore, previous research showed that when more difficult postural control conditions are present (e.g., unstable or complex balance tasks, or external perturbations), the sensory information related to dental occlusion is more strongly used (Julià-Sánchez et al., 2016, 2019; Tardieu et al., 2009). On this basis, the impacts of craniomandibular system activities, such as jaw clenching, may become more significant during dynamic or difficult balancing tasks compared with static ones.

The current thesis aims to investigate the effects of concurrent activities of the craniomandibular system on postural control in dynamic conditions, particularly during dynamic reactive balance and dynamic steady-state balance. Dynamic reactive balance can be described as compensation for unpredictable perturbations to preserve balance. These postural perturbations are primarily whole-body perturbations generated by surface translations and rotations. Dynamic steady-state balance involves fundamentally the maintenance of balance after self-initiated disturbances, such as swinging the leg forward during walking or running (Shumway-Cook & Woollacott, 2017).

The following two main topics were examined within this thesis: (1) the influence of jaw clenching on dynamic reactive balance, and (2) the influence of jaw clenching on dynamic steady-state balance. Five studies encompassing the methods of dynamic posturography together with the biomechanical analysis were carried out. The current chapter (Chapter

9) summarizes the main findings of these five studies described in the previous chapters (Chapter 4-8) and discusses the potential mechanisms of the detected effects of jaw clenching. In the last part (Section 9.3), some implications and recommendations for future research are provided.

9.1 Influence of jaw clenching on dynamic reactive balance

The studies provided in Chapters 4-6 focused on the influences of submaximal jaw clenching on dynamic reactive balance. In Chapter 4, the following research questions are issued: (1) if submaximal jaw clenching has acute enhancing effects on dynamic reactive balance compared with the habitual stomatognatic behavior condition (discussed in Section 9.1.1) ; (2) if the acute effects of jaw clenching were specifically due to neuromechanical effects of this oral-motor activity or more generally due to activities of the craniomandibular system (discussed in Section 9.1.2).

Chapter 5 deals with the research questions if the reflex activities and co-contraction behavior of the trunk and lower limb muscles change under the effects of different oral-motor tasks (discussed in Section 9.1.3), whereas Chapter 6 focused on whether the effects of jaw clenching were associated with dual-task benefits or specifically due to neuromechanical modulations associated with jaw clenching (discussed in Section 9.1.4).

9.1.1 Jaw clenching improves dynamic reactive balance performance in a direction-specific manner

The study explained in Chapter 1 revealed that submaximal jaw clenching improved dynamic reactive balance performance in one of the four possible perturbation directions compared with the tongue pressing and habitual stomatognatic behavior conditions. In the remaining three perturbation directions, no significant effects of simultaneous jaw clenching were detected. On this basis, it was concluded that submaximal jaw clenching can improve dynamic reactive balance but the occurrence of these enhancing effects was direction-specific.

In this experiment, dynamic reactive balance was assessed by using an oscillating platform that was perturbed unpredictably and randomly in one of the possible directions, these are backward, forward, ipsilateral and contralateral. The four perturbation directions were examined separately as suggested by Freyler et al. (2015) and were considered distinct tasks. The reason for this approach is that muscle spindles convey different information depending on the direction and velocity of perturbations (Akay & Murray, 2021). Furthermore, the perception, processing, and outcome of the postural responses are strongly influenced by the direction of surface translations (Freyler et al., 2015; Nonnekes et al., 2013).

The dynamic reactive balance task in this experiment was to compensate for the perturbation as fast as possible and thereby bring the oscillating platform into its neutral position. The operationalization of dynamic reactive balance performance was done by use of DR as suggested by Kiss (2011a). DR revealed how quickly the damping occurred and, therefore, how good the dynamic reactive balance performance was. The experiment results indicated that simultaneous submaximal jaw clenching led to better compensation of the perturbations, and therefore, improved the dynamic reactive balance performance only in case of forward acceleration of the oscillating platform during the initiation of the perturbation. Forward acceleration of the platform in turn led to backward sway of the body. As shown in a study investigating the effects of type and direction of perturbations (C. Chen et al., 2014), forward surface translations are less stable than backward ones. They cause faster muscle activations as well as faster and larger lower limb joint movements. Furthermore, in another study comparing backward and forward perturbations in terms of postural outputs, it was suggested that postural responses to backward and forward perturbations may be processed by different neural circuits (Nonnekes et al., 2013). The direction-specific characteristics of the results in this experiment can possibly be attributed to the neural circuits recruited during jaw clenching which are relevant for forward perturbations but not for backward ones.

For a better understanding of the improved dynamic reactive balance performance, the segmental kinematics were analyzed in the forward perturbation direction, in which significant effects of submaximal jaw clenching were detected. More precisely, the body was divided into five anatomical segments, these are head, trunk, pelvis, knee and foot, and the mean speed of these regions was calculated during the dynamic reactive balance task. The results revealed that (1) the foot had the highest mean speed among the three oral-motor task conditions, followed by the knee and the head. The mean speeds of the foot, knee, and head were higher than those of the trunk and pelvis, whereas the speeds of the trunk and pelvis did not differ from each other; (2) the mean speeds of the analyzed segments were overall lower during simultaneous submaximal jaw clenching compared with the other two oral-motor tasks.

The results showed that the trunk and pelvis exhibited the lowest mean speed across the analyzed regions. This could be attributed to proximal segments being prioritized over distal ones for stability during balance tasks (Hughey & Fung, 2005; Munoz-Martel et al., 2019). The second main finding of the segmental kinematics analysis was that jaw clenching led to lower mean speeds of the analyzed segments.

9.1.2 Tongue pressing does not lead to identical effects as jaw clenching

The tongue has a highly organized and extensive representation at various levels of the brain (Bordoni et al., 2018). Changes in tongue position were shown to have effects on the whole body, for example on cardiac function (J. E. Schmidt et al., 2009) and postural control (Alghadir et al., 2015a). Activities of the tongue were also indirectly investigated in studies focusing on chewing (Kushiro & Goto, 2011), in which the tongue supports the movement (Greet & De Vree, 1984; Lund, 1991). However, to the best of our knowledge, no study investigated the effects of tongue pressing, during which the tongue is primarily active in executing the oral-motor task.

To date, there is no consensus or clear explanation regarding the effects of jaw clenching on motor behavior. Possible explanations could be the stimulation of periodontal receptors, different proprioceptive inputs due to different jaw relations, or the facilitation of human motor system excitability (Komeilipoor et al., 2017; M. Takahashi et al., 2006). The secondary goal of the second experiment comprised in the current thesis was to investigate the effects of an instructed, controlled submaximal tongue pressing against the palate, which can also be described as stomatognatic muscle activity without occlusal loading. It was hypothesized that both submaximal jaw clenching and tongue pressing would enhance dynamic reactive balance performance. The expected enhancing effects could be explained by the neuromechanical coupling of the stomatognatic system and the postural control system (Cuccia & Caradonna, 2009; Hegab, 2015) or by the dual-task paradigm (Fraizer & Mitra, 2008). The results of the experiment revealed that submaximal pressing with the tongue seems not to have any observable effects on dynamic reactive balance performance whereas simultaneous submaximal jaw clenching improved dynamic reactive balance performance in the case of forward acceleration of the platform as explained in the previous section (Section 9.1.1). Based on these results, it was suggested that dynamic reactive balance performance improvement was not due to stomatognatic motor activity per se or the dual-task paradigm, but in particular to the submaximal clenching of jaws.

9.1.3 Co-contraction behavior does not change during simultaneous jaw clenching

Chapter 1 showed that simultaneous submaximal jaw clenching improves dynamic reactive balance in a direction-dependent manner. Particularly in the case of forward acceleration of the platform, jaw clenching was found to result in a better compensation of external perturbations. Furthermore, the segmental kinematics analysis revealed that simultaneous jaw clenching led to lower mean speeds of the analyzed body segments but did not affect the relationship between regional mean speeds.

Various studies reported some changes in reflex activities due to simultaneous jaw clenching (Miyahara et al., 1996; Takada et al., 2000; Tomita et al., 2021). Furthermore, a previous study showing the stabilizing effects of jaw clenching during static steady-state balance showed that jaw clenching may lead to changes in co-contraction patterns (Hellmann et al., 2015). On this basis, a follow-up analysis was conducted which was presented in Chapter 5. With this follow-up study, it was aimed to investigate the neuromechanical mechanisms underlying the observed jaw clenching effects on dynamic reactive balance. To accomplish this, the activity and co-contraction patterns of posture-related muscles and muscle pairs were examined before and throughout important reflex phases following forward perturbations. It was hypothesized that muscle activity and co-contraction patterns of relevant muscles and muscle pairs in reflexive phases change under the influence of simultaneous submaximal jaw clenching. The findings might ultimately help to understand the neuromechanical changes occurring under the effects of submaximal jaw clenching.

The results revealed neither before nor after perturbations significant differences in muscle activities in critical reflexive phases between the groups. This meant that simultaneous jaw clenching and tongue pressing did not seem to result in any changes in anticipatory or compensatory postural adjustments. This finding was in conflict with the hypothesis as well as with previous studies showing the facilitation of reflex responses due to jaw clenching (Miyahara et al., 1996; Takada et al., 2000; Tomita et al., 2021). Particularly, Tomita et al. (2021) showed that jaw clenching leads to an earlier onset of anticipatory postural adjustments as well as larger peaks in trunk and lower limb muscle activities both before and after perturbations. On the other hand, they did not detect any changes in CoM or CoP displacements due to jaw clenching. However, in their experiment, the participants stood bipedal on a rigid support surface and external perturbations were applied by a pendulum device (Kanekar & Aruin, 2015; Santos & Aruin, 2008), whereas, in the current study presented in this thesis the participant stood on one leg on an oscillating platform that was perturbed externally. The different results from earlier research and the current study may be explained by the task-specificity of balance (Giboin et al., 2015; Ringhof & Stein, 2018).

The results regarding the co-contraction ratios revealed some reductions under the effects of the tongue pressing. Particularly, before the perturbation and in short to medium latency phases, significant differences were detected for two muscle pairs from the upper leg and trunk. Furthermore, in the phase of late latency response, both jaw clenching and tongue pressing led to increased co-contraction for the muscle pair of calves compared with the habitual stomatognatic behavior conditions. These effects may be explained by the facilitation of corticospinal pathways under the influence of stomatognathic activities. Since, this reflex phase is modulated by the involvement of corticospinal pathways (Taube et al., 2006), and jaw clenching was shown to lead to increased facilitation of corticospinal pathways to the leg muscles (Boroojerdi et al., 2000). Nevertheless, none of the results indicated effects that were specific to the jaw clenching condition, which would have helped to explain the neuromechanical mechanisms underlying the observed jaw clenching effects on dynamic reactive balance. Based on the findings, it can be concluded that neither muscle activities nor co-contraction patterns of posture-related muscles and muscle pairs helped to elucidate the neuromechanical effects of jaw clenching which were visible in dynamic reactive balance performance (Fadillioglu et al., 2022a).

9.1.4 Automation of the jaw clenching does not have any observable effects on dynamic reactive balance

The study presented in Chapter 6 investigated the effects of submaximal jaw clenching on dynamic reactive balance task performance after 1-week of jaw clenching training. Various studies showed that jaw clenching influences balance performance under certain conditions (e.g., upright standing (Hellmann et al., 2011a; Ringhof, Leibold, et al., 2015; Tanaka et al., 2006)). However, it is not known whether these effects are related to the dual-task situation (i.e. the effects of concurrently performed additional motor tasks (Broglio et al., 2005; Fraizer & Mitra, 2008; Ghai et al., 2017) or those particular to jaw clenching.

Previous studies reported that the dual-task paradigm can be utilized to improve performance in primary motor tasks (e.g., balance tasks (Andersson et al., 2002; Broglio et al., 2005)). Thereby, a simultaneously performed secondary task sensitively directs the individuals' attention to an external source. This attentional shift allows the motor system to work automatically, resulting in improved performance in the primary motor task (Ghai et al., 2017; Polskaia et al., 2015; Swan et al., 2004; Wulf et al., 2001). However, it should be noted that a secondary task may not necessarily improve the performance in the executed tasks but can also result in no change (Choi et al., 2023) as well as performance decrements. The adverse effects can be explained by the parallel sharing of a limited set of resources (R. A. Schmidt et al., 2018). Nevertheless, a growing body of literature suggests that postural control can benefit from a dual-task situation (Andersson et al., 2002; Broglio et al., 2005; Polskaia et al., 2015; Swan et al., 2004). On this basis, it can be argued that the effects of jaw clenching on postural control are related to the dual-task paradigm but not the specific effects of the jaw clenching task.

In this study, given in Chapter 6, the aim was to evaluate whether the effects of submaximal jaw clenching are associated with general dual-task benefits or specifically due to neuromechanical connections of the stomatognathic system to the postural control system. It was hypothesized that submaximal jaw clenching specifically affects dynamic reactive balance performance, and this effect is not due to dual-task benefit. With the study design establishing an intervention group that trained the submaximal jaw clenching task three times a day during one week, it was aimed that for this group the jaw clenching task becomes an explicit task and loses its novelty. Ultimately, increased focused attention associated with a secondary novel task, therefore, the dual-task benefits would also disappear.

9.1.4.1 Effects of jaw clenching and its automation

The results revealed that neither jaw clenching nor its automation through jaw clenching training resulted in significant dynamic reactive balance performance changes as assessed by the compensation of perturbation (DR, (Kiss, 2011a)) and COM sway. These findings did not support the hypothesis of this study. On the other hand, muscle activities in reflex phases revealed some changes in jaw clenching conditions in lower leg muscles and particularly for the anterior-posterior perturbation directions but not for the medio-lateral ones. Based on these findings, it can be suggested that the submaximal jaw clenching task may result in changes in reflex activities but changes are direction-specific as well as muscle-specific. On the other hand, the postural control process is a product of complex interactions of the postural control system and comprises inter-muscular coordination patterns. Determination of individual muscle activities in certain important reflex phases may have been a limiting factor in this study. Therefore, in future studies, the coordination of multiple muscles should be investigated alongside the activity of individual muscles. For example, coordination models, such as muscular synergies, can be used to do this (D’Avella et al., 2003; Munoz-Martel et al., 2021; Ting & Macpherson, 2005).

9.1.4.2 High learning effects without balance training between sessions

A secondary important finding of this study was the high learning effects of the balance task even though there was not any balance training performed between the two measurement sessions 1-week apart. In three of the four perturbation directions, the perturbation was better compensated at the posttest compared with the pretest regardless of the groups. Furthermore, for all perturbation directions, the velocity of CoM decreased at the posttest. Even though, the participants performed familiarization trials before the measurements and no systematical dynamic reactive balance performance improvements within the measurement sessions were observed, the learning of balance task was apparently inevitable. The debate emerged as to whether the learning effects of balance task were so high that they overweighed the potential beneficial effects of jaw clenching. This question cannot be answered using the current study design and additional research is required.

9.2 Influence of jaw clenching on dynamic steady state balance

The research presented in Chapters 7-8 concentrated on the influences of submaximal jaw clenching on dynamic steady-state balance. Chapter 7 focused on the research question whether the sway, control and stability of the CoM during dynamic steady-state balance was affected by the three different oral-motor tasks, which is discussed in Section 9.2.1. The research questions issued in Chapter 8 were threefold: first, if concurrent submaximal jaw clenching improves dynamic steady-state balance (discussed in Section 9.2.2); second, if jaw clenching effects persist when the novelty of the secondary jaw clenching task, and potential dual-task benefits, decrease (discussed in Section 9.2.3); and third, if a better dynamic steady-state balance performance is associated with decreased muscle activities (discussed in Section 9.2.4).

9.2.1 Oral-motor activities do not change sway, control and stability of center of mass during dynamic steady-state balance

Controlling posture entails regulating the body's position in space in order to maintain stability and orientation. Stability is described as the ability to control the CoM with respect to the BoS, whereas orientation is the ability to maintain an adequate relationship between body segments as well as the body and its surroundings (Shumway-Cook & Woollacott, 2017). In various postural control studies, the CoM is proposed as the controlled variable, although experimental verification is difficult (Kilby et al., 2015; Nicolai & Audiffren, 2019; Richmond et al., 2021; Winter et al., 1998). For example, Scholz et al. (2007) implemented the UCM technique to see whether the CoM is the primary variable controlled by the CNS for postural control. Their findings revealed that after recovery from a loss of balance, participants tend to re-establish the position of the CoM rather than the joint configurations, implying that the CoM is the primary variable controlled by the CNS. Furthermore, the study presented in Chapter 4 revealed that the participants had less movement in their pelvis, which can be used as an approximation of the CoM (Yang & Pai, 2014), compared with the distal segments. This might be interpreted as a hint that the CNS primarily control the CoM.

In the first experiment comprised in this thesis, the participants stood one-legged on an oscillating platform, which was unexpectedly perturbed. The first three swings of the platform were considered as the phase in which the participants tried to compensate for this external perturbation (Kiss, 2011a), therefore, the dynamic-reactive balance was of great importance. The main aim in the second phase of this balance task (i.e. after the compensation of the perturbation) was to stand one-legged on the oscillating platform, therefore, dynamic steady-state balance was challenged in this phase. The study given in Chapter 1 concentrated on the dynamic steady-state phase of the balance task. This study aimed to investigate how different stomatognathic motor activities (i.e. submaximal jaw clenching, submaximal tongue pressing and habitual stomatognatic behavior) affect the sway, stability and control of the CoM during a dynamic steady-state balance task. Particularly, the sway, temporal dynamics, stability and control of CoM were investigated, which are discussed in the following sub-chapters.

9.2.1.1 Sway of CoM

The swaying behavior of the CoM is an important feature for postural control studies (Asslände et al., 2020; Richmond et al., 2021). The spatial dynamics of the CoM can be assessed among others by the total distance covered in a certain period of time (Prieto et al., 1996; Richmond et al., 2021). To assess the spatial dynamics of the CoM sway, the total distance covered in three-dimensional vector space was calculated for the following interval of 12 s after the compensation for the perturbation. The results showed no significant effects between the stomatognathic motor activities independent of the direction of the prior perturbation. This indicated that the swaying behavior of the CoM was not affected by the stomatognathic motor activities. However, it should be noted that the effect size was medium ($p = 0.182$; $\eta^2 p = 0.073$) in the direction of perturbation in which the dynamic reactive balance performance was shown to be better (discussed in 9.1.1). Eventhough a medium effect size does not have a high statistical power, jaw clenching may have effects on the dynamic steady-state balance performance but these were not high enough to be detected by using the chosen methods.

9.2.1.2 Temporal dynamics of CoM

Temporal dynamics of the CoM sway is another crucial feature regarding postural control, since fluctuations in supra-postural activity can result in both temporal and spatial changes (F. C. Chen & Stoffregen, 2012). Previous studies suggested that a DFA can measure the long-range correlations, or fractality, of the data (McGrath, 2016), therefore, DFA can be used to investigate the temporal dynamics of postural movements (Duarte & Sternad, 2008; Fink et al., 2019; Lobo da Costa et al., 2019; C. C. Wang & Yang, 2012). In this study, DFA was applied to assess the temporal dynamics of CoM sway. The scaling components, α , were used as a measure for the persistency of the sway (Lin et al., 2008). The findings revealed that the stomatognathic motor activities did not differ in terms of the temporal dynamics of the CoM sway. The scaling exponents α were larger than 1.5, suggesting a Brownian noise (McGrath, 2016), across both perturbation directions and simultaneously performed stomatognathic motor tasks. These findings indicated that the CoM sway was persistent in all conditions and the level of persistency was not affected by the stomatognathic motor activities.

9.2.1.3 Stability and control of CoM estimated by a UCM approach

The CNS must coordinate a redundant musculoskeletal system having more degrees of freedom than necessary to complete the movement tasks (Bernstein, 1967; Latash et al., 2002). Synergies are one of the different approaches used to model how CNS deals with this redundancy (D’Avella et al., 2003; Latash et al., 2007). According to Latash et al. (2007), "synergy" is a neural organization composed of a multi-element system that coordinates the distribution of a task among a group of so-called EVs. The co-variation of EVs are used to stabilize a targeted variable, the so-called PV. Thereby, there are a number of equivalent movement solutions in which the true value of PV is achieved. One option to estimate the quantity of equivalent movement solutions and the level of stability of the PV is the UCM approach (Scholz & Schöner, 1999). In this study, the UCM method was used to analyze how joint movement co-variation affects the stability and control of CoM, as measured by $\mathrm{UCM}_{\mathrm{Ratio}}$ and $\mathrm{UCM}_{\perp}$,respectively (Freitas et al., 2006; Hagio et al., 2020; Hsu et al., 2013, 2017; Krishnamoorthy et al., 2005; Scholz et al., 2007).

The findings of UCM analysis in this study revealed that the three simultaneously performed stomatognathic motor tasks did not lead to any differences in $\mathrm{UCM}_{\mathrm{Ratio}}$, This demonstrated that submaximal jaw clenching or tongue pressing did not result in a more stable CoM than habitual stomatognatic behavior conditions during dynamic steady-state balance. The results of $\mathrm{UCM}_{\perp}$ also showed no significant differences between the stomatognathic motor tasks, which indicated that simultaneously performed submaximal jaw clenching or tongue pressing did not lead to different control compared to habitual stomatognatic behavior conditions during dynamic steady-state balance.

9.2.2 Dynamic steady-state balance performance improves during simultaneous jaw clenching

The last study of this thesis, presented in Chapter 8, focused on the submaximal jaw clenching effects on dynamic steady-state balance. Dynamic steady-state balance assessment was done by use of a stabilometer. Thereby, the dynamic steady-state balance task was to keep the stabilometer platform in the horizontal position as long as possible. As a performance measure, the total time at the horizontal position was calculated, where the horizontal position was defined as ±3° deviation from the horizontal neutral position (Brueckner et al., 2019; Kiss, Brueckner, & Muehlbauer, 2018) for at least 500 ms (Giboin et al., 2015).

In the first research question of this study, the acute effects, therefore the results of the pretest, were addressed. The statistical analysis revealed that the participants could keep the platform in the horizontal position longer during simultaneous jaw clenching compared with the non-clenching condition. This demonstrated that at the pretest, all participants performed better in the dynamic steady-state balance task in the jaw clenching condition than in the non-clenching one. This finding supported the first hypothesis that dynamic steady-state balance performance improves during simultaneous jaw clenching.

In previous studies, it was shown that jaw clenching may alter static steady-state balance (Hellmann et al., 2011a, 2015; Ringhof, Leibold, et al., 2015; Ringhof, Stein, et al., 2015) and dynamic proactive balance (Tomita et al., 2021). Furthermore, the study explained in Chapter 4 revealed that jaw clenching alters balance during dynamic reactive balance in a direction-specific manner. The findings of the current study complemented the previous ones by showing the enhancing effects of simultaneous submaximal jaw clenching on dynamic steady-state balance performance.

In Section 9.2.1, the dynamic steady-state part of the balance task on the oscillating platform was analyzed. Thereby, the sway, control and stability of the CoM were investigated under the effects of different stomatognathic motor activities. The findings revealed that simultaneous submaximal jaw clenching does not influence the performance variable CoM during dynamic steady-state balance. However, the balance task was not the same but it was standing one-legged on an oscillating platform after the compensation of the perturbation, whereas in this study the participants stood bipedal on a stabilometer and tried to keep the platform parallel to the ground. Partially conflicting results from these two studies may be explained by the task-specificity of balance (Giboin et al., 2015; Ringhof & Stein, 2018). The results of one balance task are not necessarily transferable to another one but the findings should be interpreted very carefully.

Another explanation for why there were jaw clenching effects in this study and not in the previous one might be the different difficulty levels of the dynamic steady-state balance tasks. Previous studies indicated that when more difficult balance tasks are present, the sensory information related to dental occlusion is more strongly used (Julià-Sánchez et al., 2016, 2019; Tardieu et al., 2009). On this basis, it can be argued that the effects of jaw clenching may become more significant during more difficult balance tasks. Possibly the most difficult part of the balance task on the oscillating platform was the compensation of the perturbation. Afterward, the balance task was just one-legged standing on an unstable support surface, which might have been not challenging enough for healthy physically active adults. Whereas, the balance task on the stabilometer was to keep an easily tiltable platform parallel to the ground as long as possible, which was probably more difficult to execute.

9.2.3 Jaw clenching effects persist despite decreased novelty of jaw clenching task

Similar to Section 9.1.4, this part of this study aimed to understand whether the effects of jaw clenching on postural control are related to the dual-task paradigm (Andersson et al., 2002; Broglio et al., 2005; Polskaia et al., 2015; Swan et al., 2004). The study designs differed in several points, particularly in the type of balance task and intervention. In the former study, the participants executed a dynamic reactive balance task and the intervention group trained solely for jaw clenching between the pretest and the posttest. Whereas the current study comprised a dynamic steady-state balance task, and secondly, the group in which a decrease in the novelty of the jaw clenching task was expected at the posttest, trained for dynamic steady-state balance task with simultaneous jaw clenching. In other words, the participants in the current study trained for jaw clenching together with the balance task, in the form of a dual-task.

In the current study, it was hypothesized that the effects of jaw clenching on dynamic steady-state balance performance persist even if the novelty of the jaw clenching task and the increased requirement of attention due to its novelty decrease (the second hypothesis). The findings revealed that the participants could keep the stabilometer in a horizontal position longer during simultaneous submaximal jaw clenching compared to non-clenching conditions at both measurement times. This supported the second hypothesis by indicating that the dynamic steady-state balance performance was better during the jaw clenching condition compared with the non-clenching condition at the posttest further on.

A secondary finding of this study was the high learning effects of the balance task as in the previous study discussed in Section 9.1.4. In the current study, a three-armed experimental design was used, where two groups trained for the dynamic steady-state balance task in the intervention phase. One of the groups trained the dynamic steady-state balance task in classical single-task form, whereas the other one trained in the form of a dual-task, together with simultaneous jaw clenching. The third control group had no training between the pretest and the posttest. The results revealed that regardless of their training status, all of the groups improved their dynamic steady-state performance at the posttest. Interestingly, all groups increased their dynamic steady-state balance performance, with no significant group differences. This indicated that the learning effects of the balance task were high and an additonal balance training seemed not to lead any further improvement in dynamic steady-state balance performance at the posttest. This finding is noteworthy because prior research has shown that dynamic steady-state balance performance improves following balance training with the same balance task used for testing (e.g., Giboin et al., 2015; Kiss, Brueckner, & Muehlbauer, 2018). In this study, the effects of balance training may have been masked by the high learning effects of the balance task.

9.2.4 Dynamic steady-state balance performance improvement is accompanied by decreased muscle activities

The stabiliometer used in this study was also used in various studies to assess dynamic steady-state balance performance (Brueckner et al., 2019; Steib et al., 2018; Steiner et al., 2016; Taubert et al., 2010). Thereby, continuous postural adjustments are required to maintain an unstable platform in the horizontal position. In most of the studies, the dynamic steady-state balance performance was considered but the EMG data were rarely analyzed (Brueckner et al., 2019; Taubert et al., 2010). Brueckner et al. (2019) analyzed the effects of dynamic balance task training for two days and showed reduced muscle activity as well as a reduced EMG intensity in calf muscles. They explained these alterations with movement efficiency.

The third aim of the current study given in Chapter 8 was to investigate the changes in muscle activities for a deeper understanding of the adaptations occurring during a dynamic steady-state balance task with simultaneous jaw clenching. Based on the findings of Brueckner et al. (2019), it was hypothesized that better dynamic steady-state balance performance is associated with decreased muscle activity due to movement efficiency.

The results revealed that all muscle activities were less at the posttest. Given that dynamic steady-state balance performance was higher at the posttest, it may be argued that improved dynamic steady-state balance performance is related to lower muscle activities. However, only one of the examined muscles, which was a quadriceps muscle, showed a significant moderate correlation between dynamic steady-state balance performance improvement and muscle activity reduction from the pretest to the posttest. The non-significant correlations in the remaining muscles could be attributed to the linear technique used for both the calculation of changes between the two measurement times and the correlations between the parameters. For example, a previous study examining the activation of the muscles during back squats with varying weights revealed a nonlinear relationship between the changes in loads and the activations of the muscles (van den Tillaar et al., 2019). This finding suggests that the correlation between the dynamic steady-state balance performance improvements and the muscle activity reductions may be significant and larger when evaluated by using non-linear methods. Nevertheless, the dynamic steady-state balance performance increase was accompanied by decreased activity of all of the analyzed muscles. These findings were consistent with previous studies (e.g., Brueckner et al., 2019) that observed training-related reductions in muscle activities, which may be explained by improved movement efficiency. On the other hand, even though the dynamic steady-state balance performance was significantly better during simultaneous jaw clenching than in the non-clenching condition over two measurement times, the muscle activities did not demonstrate any systematic changes between the stomatognathic motor activities. Only the activity reduction of one of the analyzed calf muscles was less in the jaw clenching condition compared with the non-clenching condition between the pretest and the posttest. These findings implied that the improvement in dynamic steady-state balance performance during simultaneous jaw clenching may have been caused by additional, as of yet unidentified mechanisms in addition to movement efficiency.

9.3 Implications and recommendations

The findings of this thesis revealed the effects of submaximal jaw clenching on dynamic balance only to a limited extent. Particularly, simultaneous submaximal jaw clenching resulted in a better dynamic reactive balance, thereby, reducing the speed of the body segments but reflexive activities remained unchanged. Furthermore, through jaw clenching, dynamic steady-state could be improved but not for all dynamic steady-state balance task conditions. Importantly, the occurrence of the effects seemed not to be associated with dual-task benefits but specifically with the jaw clenching task. Considering the yet remaining contradictions and research gaps, further studies are necessary to enhance the findings reported here, ideally with different dynamic balance tasks that would have less learning effect. The current state of the research could not yet fully eliminate the uncertainty regarding the potential benefits of jaw clenching concerning balance performance under dynamic conditions.

In addition to investigating jaw clenching effects on a balance performance level, the current thesis undertook detailed biomechanical investigations to clarify the underlying neuromechanical mechanisms. The studies provided some clues but could not completely clarify these mechanisms. Future studies should aim to identify the processes behind the effects of concurrent submaximal jaw clenching. In addition, the following issues should be considered in future research:

- Experimental designs that would minimize the unwanted learning effects of balance tasks which may potentially mask the effects of jaw clenching;
- Assessment of jaw clenching effects for different groups of participants that have impaired balance (e.g., elderly, neurological patients);
- Investigation of momentaneous, but not sustained, jaw clenching to increase its real-life scenario compatibility;
- Investigation of the effects of jaw clenching in the longer term (e.g., 10-12 weeks) to ultimately examine its feasibility as a supportive tool for balance improvement in dynamic situations;
- Consideration of experimental designs in which sensory information from primary sources is reduced (e.g., eyes closed);
- Examination of synergies of posture-related muscles under the effects of jaw clenching.

10 Conclusion

The control of human posture is essential for daily life. Good balance is associated with a lower incidence of falls and accidents (Hrysomallis, 2007; Rubenstein, 2006), whereas poor balance can result in a loss of functional independence and limited participation in daily activities.

The postural control system comprises a complex interaction of multiple systems of the body. Thereby, a continuous flow of sensory inputs is used to determine the position and movement of the body in relation to its surroundings and ultimately translated into motor commands to maintain the balance in sustainedly changing situations (Shumway-Cook & Woollacott, 2017). Various factors have been shown to influence balance, including the state of the craniomandibular system. Both the positions and activities of the craniomandibular system may modulate balance. Particularly, jaw clenching has gained attention in various studies, probably because it facilitates the excitability of the human motor system like the Jendrassik manoeuvre (Boroojerdi et al., 2000; Gregory et al., 2001). In contrast to balance in more static conditions (e.g., upright standing), the influence of jaw clenching in dynamic situations (e.g., standing on unstable support surfaces) has not yet been thoroughly studied.

The present thesis addressed the above-mentioned research gap and aimed to gain a more detailed insight into the neuromechanical mechanisms of concurrent jaw clenching during dynamic balance. Thereby, the biomechanical assessment methods comprising dynamic posturography, three-dimensional motion capturing, inverse kinematics as well as EMG analysis were applied. Five research articles that were published in international peer-reviewed journals aimed to close this research gap. The results of these studies were given in Chapter 4-8 and discussed in Chapter 9, whereas in Chapter 1-3 theoretical background and important terms were introduced.

The five studies presented in this thesis revealed basically the following findings:

i. Simultaneous submaximal jaw clenching can lead to a better compensation of external perturbations and therefore, improve dynamic reactive balance but the occurrence of these effects is direction-specific. Furthermore, better perturbation compensation due to jaw clenching was accompanied by lower mean speeds of the body segments.

ii. Simultaneous submaximal tongue pressing does not seem to result in a better dynamic reactive balance performance. The detected dynamic reactive balance performance improvement during simultaneous jaw clenching was not due to stomatognatic motor activity per se or the dual-task paradigm, but in particular to the submaximal jaw clenching task.

iii. The neuromechanical impact of jaw clenching which was evident in dynamic reactive balance performance in the case of forward acceleration of the platform can not be explained by the changes in muscle activity or co-contraction patterns of posture-related muscles and muscle pairs.

iv. The automation of jaw clenching seems not to have any effects on dynamic reactive balance performance, whereas the jaw clenching task was associated with some modulations of reflex activities in lower leg muscles in a direction-specific manner. The learning effects of the dynamic reactive balance task were high, and may potentially have masked the effects of jaw clenching.

v. Neither submaximal jaw clenching nor tongue pressing influence the sway, control or stability of the CoM during dynamic steady-state balance after the compensation of perturbations on the oscillating platform.

vi. Dynamic steady-state balance performance improves with simultaneous submaximal jaw clenching during a balance task on the stabilometer, and the enhancing effects of jaw clenching persist despite the decreased novelty of the jaw clenching task. The secondary finding revealed high learning effects of the balance task which may possible have masked the effects of balance training.

vii. The dynamic steady-state balance performance improvement was accompanied by decreased activity of posture-related muscles, which can be explained by the increased movement efficiency. However, there were not any jaw clenching-related changes in muscle activities.

To sum up, from the standpoints of basic and applied research, postural control is a crucial and multidisciplinary area of study. Research from various fields, including sports science, biomechanics and neuroscience, has contributed significantly to the understanding of postural control processes. The present thesis added another puzzle piece to the whole picture by discovering the effects of jaw clenching on balance in dynamic situations, albeit not yet completely. More research is needed to fully assess the potential of the jaw clenching task and to better understand the underlying neuromechanical impacts.

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Appendix

Supplementary material

S1 Table1: Mean speed of the five anatomical regions given as mean and standard deviation (SD) for different groups. JAW: jaw clenching, TON: tongue pressing, HAB: habitual jaw position.

		Head	Trunk	Pelvis	Foot	Knee
		in mm/s	in mm/s	in mm/s	in mm/s	in mm/s
JAW	Mean	33.82	27.68	29.41	107.40	78.88
	SD	9.72	7.02	7.54	19.02	12.20
TON	Mean	46.12	32.64	34.06	129.71	92.21
	SD	23.22	9.43	7.72	27.44	18.38
HAB all	Mean	47.79	33.75	35.03	124.70	87.91
	SD	19.50	9.53	9.38	27.41	18.43
HAB w/o clen-ching	Mean	42.01	31.66	33.11	118.99	84.88
	SD	12.87	7.85	6.75	22.67	17.74
HAB with clen-ching	Mean	72.81	42.80	43.32	149.47	101.07
	SD	26.47	12.64	16.11	37.67	18.44

S2 Table 1: iEMG of all muscles in MVC% · ms for four critical phases.

Muscle pair	Group		PRE	SLR	MLR	LLR
PL	JAW	Mean	18.64	17.46	19.92	18.90
		SD	12.15	10.36	13.25	13.27
	HAB	Mean	35.57	25.31	37.62	43.69
		SD	82.52	50.16	74.04	90.84
	TON	Mean	17.61	25.79	16.44	14.90
		SD	27.81	50.98	11.64	11.72
SOL	JAW	Mean	16.39	14.67	13.30	15.55
		SD	7.10	8.20	6.01	7.46
	HAB	Mean	15.42	18.88	14.67	12.04
		SD	12.14	23.70	13.49	7.47
	TON	Mean	14.44	12.84	14.17	12.24
		SD	5.66	5.66	7.39	5.38
GM	JAW	Mean	16.42	13.42	13.10	15.44
		SD	10.48	7.98	7.25	8.33
	HAB	Mean	15.75	21.49	17.47	13.96
		SD	10.48	18.89	14.30	9.74
	TON	Mean	18.82	18.20	16.47	16.81
		SD	10.79	12.71	9.74	10.76
TA	JAW	Mean	9.63	9.99	10.86	9.60
		SD	5.85	6.45	7.11	6.94
	HAB	Mean	7.09	5.77	6.39	6.19
		SD	5.28	4.44	4.15	3.92
	TON	Mean	8.70	9.33	9.61	8.60
		SD	6.70	6.12	6.61	6.02
VM	JAW	Mean	3.23	3.22	3.58	3.52
		SD	2.50	2.42	3.07	2.74
	HAB	Mean	7.21	7.00	6.17	5.04
		SD	13.50	12.54	10.89	6.21
	TON	Mean	2.73	2.86	2.54	2.76
		SD	2.86	2.85	2.88	3.14

RF	**JAW**	**Mean**	3.44	3.62	3.07	3.26
		SD	2.55	2.59	2.00	2.20
	HAB	**Mean**	2.02	1.52	2.22	1.81
		SD	1.71	1.27	1.61	1.43
	TON	**Mean**	3.74	3.20	3.60	3.68
		SD	2.89	2.66	2.80	3.18
BF	**JAW**	**Mean**	2.11	2.10	1.95	2.09
		SD	2.33	2.29	2.37	2.33
	HAB	**Mean**	1.89	1.97	2.16	1.99
		SD	1.80	1.56	1.98	1.83
	TON	**Mean**	2.12	2.14	2.01	2.06
		SD	1.92	1.87	1.51	1.49
SEM	**JAW**	**Mean**	4.05	3.17	4.07	4.28
		SD	3.34	3.64	3.91	3.20
	HAB	**Mean**	3.79	3.76	3.39	3.96
		SD	3.86	4.19	2.93	4.29
	TON	**Mean**	3.88	4.12	4.69	3.81
		SD	4.56	5.11	6.41	4.63
FL	**JAW**	**Mean**	5.49	5.01	5.83	5.70
		SD	8.97	6.98	10.15	9.05
	HAB	**Mean**	4.27	4.21	4.35	3.47
		SD	3.54	3.90	3.60	2.50
	TON	**Mean**	5.31	4.82	5.56	4.66
		SD	4.15	3.92	4.66	2.79
ABS (d)	**JAW**	**Mean**	0.86	0.78	0.75	0.96
		SD	0.57	0.62	0.43	0.75
	HAB	**Mean**	1.14	1.02	1.08	0.90
		SD	1.12	0.74	1.07	0.76
	TON	**Mean**	1.81	1.70	1.78	1.75
		SD	1.86	1.60	1.72	1.86
ABS (nd)	**JAW**	**Mean**	0.98	0.97	1.18	1.01
		SD	0.71	0.78	1.08	0.70
	HAB	**Mean**	1.20	1.29	1.26	1.27
		SD	1.03	1.51	1.14	1.15
	TON	**Mean**	1.86	1.89	1.65	1.50
		SD	2.10	2.56	1.92	1.55

OBL (d)	**JAW**	**Mean**	2.67	2.37	2.61	2.60
		SD	1.29	1.36	1.53	1.43
	HAB	**Mean**	2.18	2.22	2.16	2.00
		SD	1.01	1.32	1.38	1.20
	TON	**Mean**	3.51	4.00	3.70	4.08
		SD	3.13	3.55	3.51	3.83
OBL (nd)	**JAW**	**Mean**	3.06	2.66	3.25	3.17
		SD	1.88	1.87	2.78	2.12
	HAB	**Mean**	2.91	2.76	3.09	2.91
		SD	1.52	1.75	2.69	1.68
	TON	**Mean**	4.42	4.24	4.12	4.06
		SD	5.62	4.37	4.22	4.56
ES (d)	**JAW**	**Mean**	3.94	3.36	3.86	4.02
		SD	3.42	2.86	3.81	3.87
	HAB	**Mean**	4.04	4.39	3.93	3.71
		SD	2.99	3.59	3.27	2.73
	TON	**Mean**	7.76	6.51	7.18	6.04
		SD	11.57	8.82	9.45	7.01
ES (nd)	**JAW**	**Mean**	3.21	3.30	3.02	3.24
		SD	2.93	3.03	2.18	3.12
	HAB	**Mean**	3.12	3.04	3.39	3.18
		SD	2.09	2.03	2.36	2.58
	TON	**Mean**	6.95	6.66	6.35	5.11
		SD	11.33	10.10	10.02	6.35
Mass	**JAW**	**Mean**	4.94	4.75	4.92	4.91
		SD	3.01	2.99	3.12	2.86
	HAB	**Mean**	1.36	1.20	1.11	1.38
		SD	3.04	2.62	2.32	2.97
	TON	**Mean**	3.35	3.52	3.19	3.34
		SD	2.32	2.57	2.05	2.20

PRE: the time window just before the perturbation onset (–100 to 0 ms); **SLR:** short latency response (30 to 60 ms); **MLR:** medium latency response (60 to 85 ms); **LLR:** long latency response (85 to 120 ms). **SD** = standard deviation. **GM** = M. gastrocnemius medialis, **SOL** = M. soleus, **TA** = M. tibialis anterior, **PL** = M. peroneus longus, **FL** = M. tensor fascia latae, **SEM** = M. semitendinosus, **BF** = M. biceps femoris, **RF** = M. rectus femoris, **VM** = M. vastus medialis, **OBL** = Mm. obliquus externus, **ABS** = Mm. rectus abdominis, **ES** = Mm. erector spinae iliocostalis. **d** = dominant. **nd** = non-dominant.

S2 Table 2: Co-contraction ratio (CCR) of selected muscle pairs for four critical.

Muscle pair	Group		PRE	SLR	MLR	LLR
GM-TA	JAW	Mean	0.32	0.33	0.32	0.32
		SD	0.06	0.07	0.07	0.06
	HAB	Mean	0.30	0.28	0.31	0.30
		SD	0.06	0.09	0.06	0.07
	TON	Mean	0.31	0.32	0.32	0.31
		SD	0.08	0.08	0.09	0.10
SOL-TA	JAW	Mean	0.33	0.33	0.33	0.32
		SD	0.05	0.06	0.06	0.05
	HAB	Mean	0.31	0.30	0.31	0.33
		SD	0.07	0.08	0.07	0.08
	TON	Mean	0.33	0.33	0.32	0.33
		SD	0.08	0.08	0.08	0.09
TA-BF	JAW	Mean	0.26	0.26	0.24	0.25
		SD	0.08	0.10	0.10	0.09
	HAB	Mean	0.26	0.30	0.27	0.26
		SD	0.07	0.07	0.07	0.08
	TON	Mean	0.26	0.27	0.26	0.27
		SD	0.10	0.10	0.11	0.09
VM-BF	JAW	Mean	0.32	0.32	0.32	0.33
		SD	0.08	0.08	0.10	0.08
	HAB	Mean	0.30	0.32	0.30	0.31
		SD	0.07	0.09	0.09	0.07
	TON	Mean	0.32	0.33	0.32	0.32
		SD	0.04	0.05	0.05	0.06
RF-BF	JAW	Mean	0.30	0.28	0.29	0.30
		SD	0.10	0.10	0.09	0.10
	HAB	Mean	0.33	0.33	0.31	0.33
		SD	0.05	0.05	0.06	0.05
	TON	Mean	0.31	0.30	0.31	0.31
		SD	0.08	0.08	0.08	0.08

GM-RF	**JAW**	**Mean**	0.25	0.27	0.27	0.26
		SD	0.09	0.09	0.09	0.11
	HAB	**Mean**	0.22	0.19	0.24	0.23
		SD	0.09	0.11	0.11	0.08
	TON	**Mean**	0.26	0.25	0.25	0.26
		SD	0.11	0.13	0.13	0.13
PL-SOL	**JAW**	**Mean**	0.34	0.34	0.33	0.35
		SD	0.04	0.05	0.07	0.05
	HAB	**Mean**	0.33	0.35	0.34	0.30
		SD	0.04	0.06	0.07	0.06
	TON	**Mean**	0.34	0.33	0.34	0.35
		SD	0.05	0.06	0.06	0.05
VM-SEM	**JAW**	**Mean**	0.32	0.31	0.29	0.33
		SD	0.05	0.06	0.08	0.07
	HAB	**Mean**	0.33	0.29	0.32	0.32
		SD	0.06	0.06	0.07	0.07
	TON	**Mean**	0.27	0.28	0.28	0.27
		SD	0.08	0.09	0.10	0.08
ABS-ES (d)	**JAW**	**Mean**	0.30	0.28	0.29	0.29
		SD	0.13	0.12	0.12	0.12
	HAB	**Mean**	0.29	0.30	0.29	0.27
		SD	0.11	0.10	0.09	0.09
	TON	**Mean**	0.30	0.30	0.29	0.29
		SD	0.11	0.10	0.11	0.10
ABS-ES (nd)	**JAW**	**Mean**	0.30	0.28	0.28	0.31
		SD	0.11	0.10	0.09	0.10
	HAB	**Mean**	0.30	0.29	0.29	0.28
		SD	0.11	0.12	0.11	0.10
	TON	**Mean**	0.31	0.31	0.31	0.32
		SD	0.12	0.11	0.12	0.10
SEM-FL	**JAW**	**Mean**	0.28	0.27	0.27	0.31
		SD	0.08	0.10	0.09	0.07
	HAB	**Mean**	0.32	0.31	0.31	0.31
		SD	0.05	0.05	0.07	0.06
	TON	**Mean**	0.29	0.29	0.28	0.29
		SD	0.07	0.08	0.10	0.08

OBL-ES (d)	**JAW**	**Mean**	0.36	0.38	0.37	0.36
		SD	0.06	0.07	0.07	0.06
	HAB	**Mean**	0.39	0.37	0.37	0.38
		SD	0.06	0.07	0.07	0.07
	TON	**Mean**	0.32	0.31	0.30	0.32
		SD	0.09	0.08	0.09	0.09
OBL-ES (nd)	**JAW**	**Mean**	0.34	0.33	0.34	0.33
		SD	0.10	0.09	0.08	0.08
	HAB	**Mean**	0.36	0.36	0.36	0.37
		SD	0.06	0.07	0.08	0.07
	TON	**Mean**	0.33	0.32	0.35	0.35
		SD	0.08	0.07	0.11	0.09

PRE: the time window just before the perturbation onset (–100 to 0 ms); **SLR:** short latency response (30 to 60 ms); **MLR:** medium latency response (60 to 85 ms); **LLR:** long latency response (85 to 120 ms). **SD =** standard deviation. **GM =** M. gastrocnemius medialis, **SOL =** M. soleus, **TA =** M. tibialis anterior, **PL =** M. peroneus longus, **FL =** M. tensor fascia latae, **SEM =** M. semitendinosus, **BF =** M. biceps femoris, **RF =** M. rectus femoris, **VM =** M. vastus medialis, **OBL =** Mm. obliquus externus, **ABS =** Mm. rectus abdominis, **ES =** Mm. erector spinae iliocostalis. **d =** dominant. **nd =** non-dominant.

S3 Table1: Descriptive data used in this study represented as mean ± standard deviation. TAE: Time at equilibrium; TA: tibialis anterior, GM: gastrocnemius medialis, RF: rectus femoris, BF: biceps femoris.

		T1		T2	
		Jaw clenching	**Non-clenching**	**Jaw clenching**	**Non-clenching**
TAE in s	**JBT**	15.8 ± 6.1	14.0 ± 5.8	21.7 ± 4.2	20.8 ± 3.6
	OBT	16.0 ± 6.0	14.9 ± 5.2	21.9 ± 3.9	21.5 ± 4.0
	CON	15.8 ± 5.9	14.3 ± 8.1	19.0 ± 6.8	18.5 ± 7.1
iEMG of TA in %	**JBT**	10.8 ± 5.9	11.2 ± 7.9	5.2 ± 4.0	3.9 ± 3.3
	OBT	10.6 ± 8.5	9.3 ± 7.9	4.0 ± 4.4	3.2 ± 3.1
	CON	12.0 ± 15.9	10.4 ± 11.3	6.2 ± 5.6	6.9 ± 5.5
iEMG of GM in %	**JBT**	6.7 ± 6.5	5.8 ± 6.1	4.2 ± 4.7	4.2 ± 5.5
	OBT	7.9 ± 8.7	7.3 ± 6.8	2.9 ± 2.8	3.2 ± 2.6
	CON	8.6 ± 6.4	8.3 ± 6.7	4.7 ± 3.3	5.5 ± 4.6
iEMG of RF in %	**JBT**	7.4 ± 6.4	6.9 ± 5.5	4.0 ± 3.0	4.2 ± 3.3
	OBT	7.1 ± 6.6	6.6 ± 6.7	3.1 ± 3.0	2.8 ± 3.0
	CON	6.6 ± 5.4	5.3 ± 3.5	4.1 ± 3.1	4.3 ± 3.5
iEMG of BF in %	**JBT**	3.7 ± 1.9	3.6 ± 2.3	2.1 ± 2.1	2.1 ± 2.3
	OBT	4.7 ± 3.8	4.0 ± 3.2	2.4 ± 2.3	2.4 ± 2.1
	CON	3.6 ± 2.0	4.4 ± 3.2	2.5 ± 1.6	2.7 ± 1.3

Statutory Declaration

Hiermit erkläre ich, dass ich die vorliegende Dissertation mit dem Titel

> „Influence of the Craniomandibular System on Human Postural Control with Special Consideration of Dynamic Stability"

selbständig angerfertigt wurde und keine anderen als die angegebenen Hilfsmittel benutzt sowie die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und die Satzung des Karlsruher Instituts für Technologie (KIT) zur Sicherung guter wissenschaftlicher Praxis beachtet habe. Diese Arbeit wurde nicht bereits anderweitig als Prüfungsarbeit verwendet.

Karlsruhe, den 15.12.2024

Cagla Kettner (née Fadillioglu) has a background in mechanical engineering and pursued her master's degree in sports sciences at the Karlsruhe Institute of Technology, where she later earned her PhD. Her research focuses on human postural control, running biomechanics, and performance diagnostics using state-of-the-art methods and technologies. Her work spans fundamental research and applied studies, bridging the gap between engineering and sports science. She has contributed to various research projects, including the influence of the craniomandibular system on dynamic balance, the biomechanics of running with different shoe configurations, and performance diagnostics in recurve archery. In addition to her research, Cagla is actively involved in teaching courses on biomechanics, training science, and data analysis. With a lifelong passion for sports, including basketball, track & field, and windsurfing, she brings a dynamic perspective to her scientific endeavors.

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