Effects of Concurrent Jaw Clenching on Human Postural Control and Sports Performance

Biomechanical Studies of Static and Dynamic Postural Control and Performance Analysis in Golf

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Summary

Maintaining balance and to properly orient the body with respect to the environment are fundamental aspects of daily living. An adequate balance control comprises not only the maintenance of balance during upright quiet stance (*static stability*) but also the recovery of balance after being perturbed or when actively moving a body segment or the entire body (*dynamic stability*). In order to handle all the variable and often unpredictable environments and situations, a powerful, yet flexible, postural control system is required. Although keeping one's balance mainly operates on an unconscious (semi-)automatic level, it emerges from complex sensorimotor processes involving multisensory information and billions of neuros that continuously coordinate a plethora of interdependent and redundant muscles and joints.

In recent years, interrelations of dental occlusion with body posture and balance became a controversial topic in literature. In fact, neuroanatomical connections between the craniomandibular system and structures involved in the postural control process have been shown. Furthermore, neurophysiologic influences of jaw clenching which may foster human motor control and performance have been described. However, literature is sparse and due to inconsistent and weak experimental designs far from having reached a consensus. In turn, a profound understanding of the potential mechanisms underlying this interrelation is lacking. The present thesis investigates the influence of concurrent submaximal jaw clenching on human postural control. Within this framework, this thesis mainly focusses on the modulation of static and dynamic postural stability with special consideration of the underlying mechanisms on kinematic and muscular levels. Besides, the impact of jaw clenching and the potential benefits of oral splints on motor performance in golf are investigated.

This thesis comprises nine main chapters. Initially, a short preface and an outline of the thesis are depicted (Chapter 1). In Chapter 2, the theoretical and methodological fundamentals of human postural control are provided. Moreover, this chapter introduces the neuroanatomic and neurophysiologic prerequisites of its interrelations with the jaw motor system. In this context, the current state of research concerning the relation of jaw

clenching with postural stability on the one hand, and with sports performance on the other hand is briefly reviewed. Based on the research gaps deduced, Chapter 3 specifies the aims and the scope of this thesis, which will be specifically addressed in the research articles depicted in the subsequent chapters.

The study in Chapter 4 considers the modulation of static postural control by concurrent submaximal clenching activities. Postural control is well-known to be highly susceptible to alternations of internal and external environments. In particular, concurrent jaw clenching has been reported to improve static stability. However, methodological deficiencies limit the significance of these reports. Furthermore, the mechanisms underlying this potential interference are not yet understood in detail. Accordingly, this study examines the effects of concurrent jaw clenching on postural stability with special consideration of potential modifications on joint and muscular levels. The results show that clenching the jaw reduces postural sway in bipedal narrow as well as in single-leg stance compared to a non-clenching control condition. This increase in postural stability is accompanied by decreased upper body oscillations and reduced joint motions about the ankle, knee and hip joints. However, there are no modulations in postural strategies and no associations with muscular co-contraction ratios. Therefore, jaw clenching seems to increase the kinematic precision among neuromuscular control patterns but not to change the main strategy during balance control.

Chapter 5 provides a follow-up study that builds on some questions resulting from the first experiment. In fact, it remained unknown whether the effects were confounded by the lack of a habitual control condition. Furthermore, it was not clarified if postural adaptations might also be observed among active controls, e.g., fist clenching, and under more complex postural conditions. The second experiment considers those issues and compares the effects of submaximal jaw clenching with active and habitual control conditions. The subjects are investigated with feet close together on firm and foam surfaces. It is shown that postural sway is significantly reduced while jaw and fist clenching but with no differences between both activities. These results confirm the previously gained findings and suggest that concurrent muscle activity in general may modulate postural stability. This finding applies also for foam support surfaces, i.e., when the proprioceptive system is challenged.

After the previous chapters have focused on static stability, Chapter 6 presents a study that investigates the impact of jaw clenching on dynamic stability. Latter refers to maintaining balance in advance or in response to unexpected or predictable perturbations. This is an important prerequisite for many activities of daily living as, e.g., walking, reaching, or when handling sudden disturbances. Knowledge about balance control under dynamic conditions provides significant information for fall prevention. In view of this practical and scientifical value, the third study uses a balance recovery task to estimate the benefits of jaw clenching in case of forward loss of balance. Similar to the first study, concurrent jaw clenching is compared to a non-clenching control condition. The results reveal no statistically significant differences between both conditions with regard to dynamic stability and kinematic variables. This in part may have methodological reasons. Specifically, the experimental approach may have undermined the facilitating effects of clenching. Interestingly, however, while recovering balance bite forces increase, reaching its maximum around the instant of touchdown. This physiological response indicates that jaw clenching is incorporated habitually in motor control in strenuous situations and by this means may aid to maintain balance in fall situations.

The last study reported in Chapter 7 turns away from postural control moving the focus on sports performance. In particular, this study examined whether jaw clenching and the use of oral splints could help to improve golfers' performance. The foundation for this experiment is twofold. First, oral splints have aroused increasing interest and application in sports, specifically in golf. Second, jaw clenching and the use of jaw-aligning appliances have been reported to induce performance enhancements, particularly of muscle strength. The present study employs competitive golfers, investigating the impact of submaximal jaw clenching and the use of oral splints on their shot length and shot precision. Golf shot analyses reveal that jaw clenching has no impact, positive or negative, on the golfers' performance compared to golf shots under habitual conditions. Concomitantly, this study shows that clenching effects are not superior for biting on an oral splint than for biting on one's teeth.

Chapter 8 finally provides a general discussion of the presented work. Herein, the depicted findings are conflated, offering a broader perspective of postural control and motor performance under the impact of clenching activities. In essence, this thesis provides further evidence towards the impact of the jaw motor system on static postural control, but it does not ascertain the underlying mechanisms of this facilitation. Therefore, explanatory approaches from diverse perspectives must be taken into consideration. In this context, increased (sub-)cortical excitation as well as dual-task interferences might provide plausible explanations. Notwithstanding this, ergogenic effects on dynamic stability and golf performance did not appear. However, the spontaneous jaw muscle activity found during falling and golf shots emphasizes its involvement in strenuous activities to augment the activation of targeted muscle groups and hence the performance of the athlete. In view of this valuable field of research, implications and recommendations for future research are deduced.

The thesis closes with a general conclusion of the present work (Chapter 9).

Zusammenfassung

Das posturale Gleichgewicht zu halten und die Position des Körpers und seiner Segmente kontrollieren zu können, sind fundamentale Aspekte des alltäglichen Lebens. Insbesondere für die Prävention von Stürzen sowie die Erbringung sportlicher Leistungen ist eine ausgeprägte Gleichgewichtskontrolle von essentieller Bedeutung. Neben der Gleichgewichtskontrolle im ruhigen Stand (*statische Stabilität*) umfasst diese gleichermaßen die Beibehaltung bzw. Wiederherstellung der Balance im Rahmen willkürlicher Bewegungen oder infolge des Einwirkens äußerer Kräfte (*dynamische Stabilität*). Zur Bewältigung dieser variablen und oft unvorhersehbaren Situationen bedarf es eines leistungsfähigen und zugleich äußerst flexiblen posturalen Kontrollsystems. Denn obgleich die Gleichgewichtskontrolle einer weitestgehend unbewussten und automatisierten Kontrolle unterliegt, ist sie das Ergebnis eines hochkomplexen sensomotorischen Prozesses. Dieser involviert ein aus Milliarden hochvernetzter Neuronen bestehendes Zentralnervensystem, welches fortlaufend über diverse sensorische Kanäle mit afferenten Informationen versorgt wird. Auf Grundlage dieser zentral integrierten Informationen werden motorische Kommandos generiert, die wiederum ein Muskelskelettsystem – bestehend aus einer Vielzahl abhängiger und redundanter Muskeln und Gelenkfreiheitsgrade – koordinieren, um schließlich die in der Interaktion mit der Umwelt gewünschte Effekte zu erzielen.

Wechselseitige biomechanische Zusammenhänge zwischen der posturalen Kontrolle und dem craniomandibulären System sind in den letzten Jahren zu einem kontroversen Thema in der Wissenschaft geworden. Basierend auf neuroanatomischen Vernetzungen wurden vielfältige Phänomene physiologischer Beißaktivitäten, die zu einer Verbesserung der motorischen Kontrolle sowie der motorischen Leistungsfähigkeit beitragen können, beschrieben. Gegenwärtig ist der Forschungsstand allerdings noch überschaubar, zumal es aufgrund inkonsistenter und teilweise mangelhafter experimenteller Designs keine einheitlichen Befunde gibt. Hinzu kommt, dass die Mechanismen, die dieser möglichen Wechselwirkung zugrunde liegen könnten, noch nicht abschließend erforscht sind. Den aufgezeigten Forschungslücken folgend werden in dieser Arbeit die Einflüsse simultaner submaximaler Beißaktivitäten auf die posturale Kontrolle sowie die Leistung im

Golfsport untersucht. Der Fokus dieser Thesis liegt dabei in erster Linie auf der Modulation der statischen und dynamischen Stabilität sowie den zugrundeliegenden Mechanismen auf kinematischer und muskulärer Ebene.

Die vorliegende Dissertation umfasst neun Kapitel. Nach einem kurzen Vorwort und Abriss über den Gegenstand der Dissertation (Kapitel 1) werden in Kapitel 2 die theoretischen und methodischen Grundlagen für das Verständnis der posturalen Kontrolle aufgearbeitet. Darüber hinaus gibt dieses Kapitel einen Einblick in die neuroanatomischen, physiologischen und biomechanischen Zusammenhänge zwischen der posturalen Kontrolle und dem Kausystem. Vertiefend wird hierzu der aktuelle Forschungsstand skizziert. Der Fokus liegt dabei in erster Linie auf den Relationen zwischen dem Zähnepressen und der posturalen Stabilität sowie dem Zusammenhang mit der sportlichen Leistungsfähigkeit. Aus den hieraus abgeleiteten Forschungslücken werden in Kapitel 3 die Ziele und Fragestellungen der Dissertation spezifiziert, welche anschließend im Rahmen der in Kapitel 4 bis 7 vorgestellten Forschungsarbeiten näher beleuchtet werden.

Die Studie in Kapitel 4 betrachtet die Modulation der statischen posturalen Kontrolle infolge simultan ausgeführter submaximaler Beißaktivitäten. Grundlage für diese Arbeit ist, dass kleinste Veränderungen interner oder externer Bedingungen die posturale Kontrolle beeinflussen können. So gibt es Hinweise dafür, dass physiologische Beißaktivitäten eine stabilisierende Wirkung haben. Die Aussagekraft dieser Studien ist jedoch limitiert, zumal die zugrundeliegenden Mechanismen bis heute nicht im Detail geklärt sind. Unter Anwendung biomechanischer Messverfahren untersucht diese Studie daher den Einfluss simultaner Beißaktivitäten auf die posturale Kontrolle und speziell die zugrundeliegenden Veränderungen auf koordinativer und muskulärer Ebene. In Einklang mit der gegenwärtigen Literatur werden für das Zähnepressen, im Vergleich zu einer nicht-beißenden Kontrollbedingung, signifikant reduzierte Körperschwankungen festgestellt – sowohl im geschlossenen Beidbeinstand wie auch im Einbeinstand. Die verbesserte posturale Stabilität geht mit reduzierten Schwankungen des Oberkörpers und geringeren Gelenkbewegungen im Bereich des Sprung-, Knie- und Hüftgelenks einher. Modifikationen der posturalen Strategien oder Korrelationen mit muskulären Co-Kontraktionsmustern werden hingegen nicht beobachtet. Folglich scheint das Zähnepressen keine Änderungen der grundlegenden Kontrollstrategien zu induzieren, aber möglicherweise eine erhöhte Präzision innerhalb der internen neuromuskulären Steuerungs- und Regelungsprozesse zu bewirken.

Kapitel 5 beinhaltet eine Folgeuntersuchung, die angesichts einiger Fragen, die aus der ersten Studie resultierten, durchgeführt wurde. So konnte die erste Studie beispielsweise nicht eindeutig klären, ob das Fehlen einer habituellen Kontrollbedingung die Ergebnisse zugunsten der Beißbedingung beeinflusst haben könnte. Weiterhin blieb ungewiss, ob posturale Adaptationen auch durch vergleichbare Aktivitäten anderer Muskelgruppen oder auf instabilen Unterstützungsflächen hervorgerufen werden könnten. Diese Fragestellungen werden in der zweiten Studie adressiert. Speziell werden die Einflüsse submaximalen Beißens mit denen einer habituellen und aktiven Kontrollbedingung verglichen und darüber hinaus die Effekte auf stabiler und instabiler Unterstützungsfläche untersucht. Dabei zeigt sich, dass sowohl das Zusammenpressen der Zähne als auch das der Faust zu signifikanten Reduktionen der Körperschwankungen führt. Zwischen diesen beiden Bedingungen werden jedoch keine statistischen Unterschiede nachgewiesen. Somit bestätigen diese Ergebnisse die zuvor gemachten Befunde und legen ferner nahe, dass die posturale Stabilität generell durch simultane Aktivität entfernt gelegener Muskelgruppen moduliert werden kann. Diese Einflüsse bestehen nicht nur auf stabiler, sondern auch auf instabiler Unterstützungsfläche.

Während die vorangegangenen Studien die statische Stabilität untersuchten, konzentriert sich die Studie in Kapitel 6 auf die beißbedingte Beeinflussung der dynamischen Stabilität. Die dynamische Stabilität beschreibt die Beibehaltung des posturalen Gleichgewichts während und nach Perturbationen. Diese Störungen der Balance können in Form willkürlicher Segmentbewegungen vorhersehbar sein, als Resultat externer Kräfte aber auch unerwartet auftreten. Insofern stellt die dynamische Stabilität eine wichtige Voraussetzung für die Bewältigung vieler Alltagsaktivitäten dar, wie z. B. beim Gehen, Greifen oder Ausgleichen plötzlicher Perturbationen. Folglich kann die Untersuchung der Gleichgewichtskontrolle unter dynamischen Bedingungen wichtige Informationen für die Sturzprävention und Rehabilitation liefern. In Anbetracht dieser praktischen und wissenschaftlichen Bedeutung wird in der dritten Studie ein experimenteller Ansatz zur Untersuchung des Einflusses von Beißaktivitäten auf die Wiedererlangung des Gleichgewichts nach einem simulierten Sturz eingesetzt. Wie in der ersten Studie wird auch hier die Bedingung des simultanen submaximalen Beißens mit einer offenen Kieferstellung verglichen. Allerdings ergeben sich weder hinsichtlich der dynamischen Stabilität noch mit Blick auf die Gelenkwinkel oder räumlich-zeitlichen Schrittvariablen signifikante Unterschiede zwischen diesen beiden Bedingungen. Ursächlich hierfür könnte unter anderem das experimentelle Vorgehen sein. Insbesondere könnte die vorgeneigte Ausgangsposition dazu geführt haben, dass die dem Beißen zugeschriebenen neurophysiologischen Effekte durch die natürliche Anspannung in Erwartung des Sturzes abgeschwächt oder vollkommen unterlaufen werden. Interessanterweise ist während der Sturzphase ein starker Anstieg der Beißkräfte zu beobachten, dessen Maximum etwa zum Zeitpunkt des initialen Bodenkontakts des Ausgleichsschritts auftritt. Das Zusammenpressen der Zähne könnte folglich eine Art physiologische Reaktion darstellen, die speziell in Situationen mit hohen Kraftanforderungen zum Tragen kommt und auf diese Weise zur Wiedererlangung des Gleichgewichts in Sturzsituationen beitragen könnte.

Die letzte Studie in Kapitel 7 richtet ihren Fokus auf die Beeinflussung der sportlichen Leistungsfähigkeit. Speziell untersucht diese Studie, ob Beißaktivitäten und die Nutzung von Beißschienen zur Leistungssteigerung von Golfern beitragen können. Diese Fragestellung ist in zweierlei Hinsicht von besonderem Interesse. Zum einen erfahren Beißschienen speziell im Golfsport zunehmende Verbreitung. Zum anderen liegen Untersuchungen vor, die eine Leistungssteigerung – speziell der muskulären Kraftfähigkeiten – durch das Tragen korrigierender Beißvorrichtungen sowie das Ausführen von Beißaktivitäten vermuten lassen. Gegenstand dieser Studie ist es daher, die Schlaglänge und -präzision bei Leistungssportlern aus der Sportart Golf während submaximaler Beißaktivitäten und des Tragens handelsüblicher Beißschienen zu untersuchen. Die Analysen zeigen, dass die Leistung der Golfer weder positiv noch negativ durch die Beißaktivität beeinflusst werden. Darüber hinaus ist es statistisch unerheblich, ob die Golfer während der Schläge eine Beißschiene tragen oder auf ihre Zähne beißen. Dennoch sind auch in dieser Studie selbst unter habituellen Bedingungen physiologische Beißaktivitäten während der Golfschläge zu beobachten.

Kapitel 8 liefert schließlich eine allgemeine Diskussion der zuvor beschriebenen Forschungsergebnisse. In diesem Zusammenhang werden die einzelnen Befunde zusammengeführt, um auf dieser Basis eine umfassendere Betrachtung der posturalen Kontrolle sowie der motorischen Leistung unter dem Einfluss von Beißaktivitäten zu ermöglichen.

Im Wesentlichen liefert die vorliegende Dissertation weitere Nachweise für den Einfluss des Kausystems auf die statische posturale Kontrolle. Die Mechanismen, die dieser Stabilisierung zugrunde liegen, können jedoch nicht abschließend identifiziert werden. Angesichts der weiterhin ungeklärten Wirkmechanismen, müssen alternative Erklärungsansätze affiner Disziplinen herangezogen werden. In diesem Kontext sind eine gesteigerte Erregbarkeit kortikaler und subkortikaler Strukturen oder dual-task Effekte in Betracht zu ziehen. Zur Klärung dieser Annahmen bedarf es jedoch weiterer wissenschaftlicher Untersuchungen. In Bezug auf die dynamische Stabilität sowie die Performance im Golf können die stabilisierenden und leistungssteigernden Effekte der Beißaktivitäten nicht bestätigt werden. Gleichwohl unterstreicht die spontane Beißaktivität, die während der Sturz- und Golfexperimente zu beobachten ist, die mögliche Bedeutung und Mitwirkung des Kausystems bei anspruchsvollen Belastungen. Möglicherweise handelt es sich hierbei um eine physiologische Reaktion, die die Aktivität der Zielmuskulatur und damit die Leistungsfähigkeit des neuromuskulären Systems augmentieren kann. In Anbetracht dieses spannenden und bedeutsamen Forschungsfeldes werden einige Implikationen und Empfehlungen für zukünftige Studien abgeleitet.

Die Dissertation schließt mit einer allgemeinen Zusammenfassung der vorgelegten Arbeit (Kapitel 9).

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1 General Introduction

1.1 Preface

Postural control delineates the control of the body's position with respect to the environment for the dual purposes of balance and orientation (Macpherson & Horak, 2013). Postural control in general and balance in particular are crucial for most activities of daily living. Furthermore, they are strongly associated with the individual's risk of falling. The process of maintaining and restoring balance is faced with a complex sensorimotor control task, involving several sensory systems and requiring continual and well-coordinated adjustments. The integrity of the systems and interactions controlling balance and orientation is collectively referred to as the *postural control system* (Shumway-Cook & Woollacott, 2007).

To appreciate the complexity of postural control, imagine the scenario of standing at the bus stop and writing a text message while waiting for the bus. Even as the mind is occupied with composing the message, unconscious processes enable humans to maintain an upright stable stance, balancing the entire body over a small base of support. The same applies to the maintenance of balance while standing in the moving bus and the driver suddenly needs to break. Whereas the feet, which are in contact with the bus, are also slowed down, initial forces cause the rest of the body to continuously head in the direction of driving. Consequently, time and precision constraints for balance recovery are dramatically increased. Nonetheless, distinct sensorimotor processes still allow humans to prevent falling by taking rapid target-oriented steps. These two examples – upright unperturbed stance while text messaging and reactive balance recovery after perturbation – illustrate very clearly the relevance but also the challenge of human postural control.

Despite its unconscious and highly automated character, the control of posture is highly vulnerable towards a multitude of internal and external factors. The absence of sensory information, neuromuscular deficiencies or external obstacles and forces can dramatically impede the control process (Horak, 2006). Unless appropriate adjustments are available, balance and orientation are decreased, which finally increases the individuals' risk of falling. In elderly, this susceptibility is additionally fostered by the degenerative decline of the sensory and neuromuscular systems (Granacher et al., 2011b). Therefore, falls are commonly observed events, particularly in the elderly but also in patients suffering from sensorimotor deficiencies. In turn, falls and its medical consequences present a major threat to the quality of life that ultimately can lead to the loss of independence or even to death (Blake et al., 1988). Investigations on postural control and its influential factors for various fields are thus a particular issue of concern.

Seeking for optimal motor control and performance, it is interesting to note that during challenging tasks, e.g., while landing following a jump, humans commonly activate remote muscle groups (Ebben et al., 2008). To unravel the significance of this phenomena, investigations on the impact of remote voluntary contractions in general and jaw muscle contractions in particular have become a central focus of research (Michelotti et al., 2011; Manfredini et al., 2012). Within this framework, concurrent jaw clenching activities were shown to contribute to increased muscular strength (Forgione et al., 1991; Ebben, 2006) as well as to improved postural control (Hellmann et al., 2011c). Concerning the latter, neuroanatomical connections and projections to several structures associated with the postural control system were suggested to form the basis for this ergogenic advantage (Cuccia & Caradonna, 2009). Yet, the underlying neuromuscular mechanisms remain unknown and the discussion as to whether body posture and dental occlusion are functionally interrelated is far from having reached a consensus.

For this purpose, the present thesis investigates the effects of concurrent submaximal jaw clenching on human postural control and motor performance. In particular, the biomechanical features of this interrelation with respect to static and dynamic postural control, as well as the potential performance gains of jaw clenching and oral splints with regard to sports performance are focused in this thesis. A profound understanding of the features and underlying processes gathered by this work could constitute an important prerequisite for fall prevention, clinical assessments, and sports promotion, as well as for future fundamental and applied research in this context.

1.2 Outline of the thesis

The present thesis covers nine main chapters. Initially, the theoretical and methodological fundamentals of human postural control are provided (Chapter 2). Furthermore, this chapter briefly reviews the current state of knowledge about the interrelation of the postural control system with the jaw motor system in general and with jaw clenching in particular. Based on the unresolved research questions deduced from the literature, Chapter 3 introduces the aims and the scope of the present thesis.

The subsequent Chapters 4 to 7 encompass four research articles that specifically address the previously deduced research questions. Each of the research articles has been published in an international peer-reviewed journal.

- Chapter 4: Modulation of Static Postural Control during Concurrent Jaw Clenching

  Ringhof, S., Stein, T., Potthast, W., Schindler, H. J. & Hellmann, D. (2015). Force-controlled biting alters postural control in bipedal and unipedal stance. *Journal of Oral Rehabilitation, 42*, 173-184.

- Chapter 5: General Modulation of Postural Sway during Concurrent Clenching

  Ringhof, S., Leibold, T., Hellmann, D. & Stein, T. (2015). Postural stability and the influence of concurrent muscle activation – Beneficial effects of jaw and fist clenching. *Gait & Posture, 42,* 598-600.

- Chapter 6: Dynamic Postural Control during Voluntary Jaw Clenching

  Ringhof, S., Stein, T., Hellmann, D., Schindler, H. J. & Potthast, W. (2016). Effect of jaw clenching on balance recovery: dynamic stability and lower extremity joint kinematics after forward loss of balance. *Frontiers in Psychology*, 7:291.

- Chapter 7: Golf Performance during Voluntary Jaw Clenching

  Ringhof, S., Hellmann, D., Meier, F., Etz, E., Schindler, H. J. & Stein, T. (2015). The effect of oral motor activity on the athletic performance of professional golfers. *Frontiers in Psychology,* 6:750.

Chapter 8 summarizes the main findings of the presented work and discusses potential mechanisms of the observed phenomena. Moreover, implications and recommendations for future research are provided. The thesis closes with a general conclusion (Chapter 9).

2 Theoretical Background

Research into postural control has considerably broadened in the last decades. Along with the increasing attention, the understanding of the postural control system, its disorders and influential factors has continuously progressed. Nonetheless, the features of postural control are still far from heaving reached a consensus, and also the neural mechanisms underlying the control of posture yet remain to be clarified (Shumway-Cook & Woollacott, 2007).

This initial section aims to provide an easy introduction to the theoretical background of this thesis. It includes a brief review of the terms and features relating to postural control, and introduces the methodological approaches for the measurement of postural stability. Furthermore, the relations of the postural control system with the functions and activities of the jaw motor system are considered as far as relevant for the subsequent work.

2.1 Postural control

Human motor control delineates the task-specific interaction of the individual with the environment and provides the basis for fundamental movements such as eating, playing and object manipulations (Schmidt & Lee, 2011). A specific form of human motor control is the control of posture. It is fundamental for most tasks of daily living and a critical aspect of the human evolutionary development. With the erection of the torso – as part of the evolution from four-legged stance and gait patterns towards a bipedal locomotion – the postural demands of human beings have dramatically increased. This adaptation requires an increased antigravity support to maintain the entire body segments at some height. Additionally, a more precise alignment of the distal body segments with respect to the gravitational vector is essential (Macpherson & Horak, 2013).

While the significance of postural control for activities such as standing and walking is generally accepted, the definitions and purposes have changed with research. Nowadays, postural control is mostly referred to the control of the body's position with respect to the environment, encompassing the dual purposes of balance and orientation (Shumway-Cook & Woollacott, 2007; Macpherson & Horak, 2013). Albeit these two components of postural control have many features in common, they are nevertheless believed to represent distinct sensorimotor processes that are controlled separately by the nervous system (Horak, 2009).

Postural orientation involves the active and appropriate alignment of the body segments with respect to each other, and between the body and the environmental surroundings for a given task (Horak & Macpherson, 1996). This capability plays an important role for optimizing the execution of movement tasks as well as for the anticipation and compensation of disturbances to postural balance. In conjunction with the erection, humans for most functional tasks established a vertical orientation of the body. This orientation requires multiple sensory references, including information about gravity, support surface and the relation to objects in the environment (Shumway-Cook & Woollacott, 2007).

The term *balance* delineates the dynamics of body posture to prevent falling (Winter, 1995). As such, it involves the active resistance to the entire internal and external forces acting on the human body in order to maintain stability (Macpherson & Horak, 2013). Therefore, the term balance is often used interchangeably with the terms *postural stability* or *postural equilibrium* (Horak, 2006; Shumway-Cook & Woollacott, 2007). In essence, the process of balance control encompasses the accurate coordination of joint movements to stabilize the body both during quiet stance as well as during self-initiated or externally triggered disturbances. As will be discussed in later sections of this chapter, this process forces the postural control system to generate and update motor commands to control the velocity and position of the center of mass (CoM) in relation to the base of support (BoS). Herein, the CoM is an imaginary point that represents the average position of the total body mass. Hence, the location of the CoM is not fixed but depends on the orientation of the entirety of body segments (Macpherson & Horak, 2013). The BoS is defined by those parts of the body that are in contact with the support surface (Shumway-Cook & Woollacott, 2007). In human stance and locomotion, the BoS usually is formed by the feet. Hence, the CoM is principally located above the BoS resembling an inverted pendulum. This mechanical instability is additionally compounded since all the body segments are linked by multiple joints with several degrees of freedom. Therefore, poor balance control is widely acknowledged as being a significant contributor to the risk of falls (Sturnieks & Lord, 2008).

In consequence, the postural control system is continuously faced to maintain antigravity support, i.e., keeping the CoM at some height, and to maintain stability, i.e., controlling the trajectory of the CoM in the horizontal plane. With respect to the former, some support is provided by bone-on-bone forces, which is assisted by tensions applied through soft tissues, ligaments, and capsules surrounding the joints. Besides, tonic contractions of antigravity muscles – primarily of lower limb, trunk and neck muscles – are mandatory to prevent the erect body from collapsing (Macpherson & Horak, 2013). Whereas low-frequency neural inputs to antagonist leg muscles groups keep the limbs extended, core and neck muscles provide the necessary synergy to maintain spine and head stability (García-Massó et al., 2016). However, this tonic activation is not sufficient for maintaining balance. By contrast, balance control requires corrective phasic muscle contractions continuously adjusted depending on the specificity of the task and the environment in order to compensate the destabilizing oscillations.

2.1.1 Static and dynamic postural stability

Concerning the task-specificity of balance control, literature commonly distinguishes between static and dynamic components of postural stability. However, a universal definition for these features has not yet been established. Some researchers relate the terms static and dynamic to the steadiness and relocation of the BoS, respectively. Others refer postural control under steady-state conditions to as static postural stability, and postural responses to applied or volitional perturbations to as dynamic postural stability (Prieto et al., 1996; Latash et al., 2003). Concerning dynamic postural stability, sometimes a further subdivision into proactive (anticipatory) and reactive (compensatory) balance control is made (Shumway-Cook & Woollacott, 2011). This thesis follows the latter approach. However, to allow a more readily access to the terminology, the terms static and dynamic stability are used.

Static stability

Static stability considers balance control under unperturbed conditions, such as while quiet standing or sitting. Mechanically, herein, maintaining balance requires the postural control system to keep the downward projection of the CoM within the BoS, whereat the area and location of the BoS are preserved throughout the entire process (Shumway-Cook & Woollacott, 2011; Macpherson & Horak, 2013). This definition of postural stability is useful as it highlights the need to always consider static stability in the context of the particular task or activity. A reduction in the size of the BoS, such as when moving from bipedal to unipedal stance, inherently means a more challenging task, requiring a greater amount of postural control (Sturnieks & Lord, 2008). Likewise, stability can be increased by using a cane or extending stance width.

Dynamic stability

Dynamic stability involves the maintenance of balance under whatever dynamic demands are made on the body, for example when stabilizing posture after sudden decelerations of the bus or when reaching to catch a ball. Hence, different scenarios under the impact of unexpected or anticipated perturbations are circumscribed. These sudden changes in postural conditions elicit perceptions of instability or actual displacements of the body CoM away from equilibrium (Horak et al., 1997). Falling is prevented by actively retrieving the CoM over the BoS or by moving the BoS under the falling CoM. Latter requires an appropriate placement of the step or grasp to control the speed and trajectory of the CoM (Macpherson & Horak, 2013). However, dynamic stability comprises not only postural responses to externally applied perturbations but also refers to balance control during self-initiated disturbances, e.g., resulting from single segment or whole body movements. A specific type of dynamic balance control during whole body movements is walking. Herein, the body is in a continuous state of imbalance, since the CoM does not stay within the BoS. To prevent a fall, the swinging foot is placed lateral to and ahead of the CoM, thus ensuring control of the CoM relative to the moving BoS (Shumway-Cook & Woollacott, 2016). Ultimately, to regain stability in dynamic conditions the BoS either can be maintained or needs to be relocated depending on the size and the type of perturbation. In the end, the outcome depends on the appropriateness of the selected postural response.

Associations between static and dynamic stability

The correlations between static and dynamic stability measures are reported to be extremely low (Granacher et al., 2011a). Therefore, different mechanisms of the postural control system are suggested to control balance under static and dynamic conditions (Shimada et al., 2003). This assumption is highly contrasting to the traditional view on the construct of postural balance. In sports and human movement science, especially in the older basic literature, postural balance has often been treated as a general ability. Nowadays, this approach is regarded critically, and recent research suggested that the principle of task-specificity also applies here (Giboin et al., 2015).

Horak et al. (2009) developed a clinical balance test battery consisting of 36 tests in six categories. The authors reported that subjects with deficiencies in one category did not score poorly in other categories. This finding is reinforced by several balance training studies showing strong performance improvements in the trained balance task but no transfer to non-trained balance tasks (e.g., McMurdo et al., 2000; Muehlbauer et al., 2012; Donath et al., 2013). Therefore, it is assumed that the capacity to balance during various balance tasks is based more on the sum of specific motor skill, rather than due to a general capacity (for review, see Kummel et al., 2016).

2.1.2 Experimental approaches for the investigation of postural stability

Numerous clinical and biomechanical methods have been introduced in recent decades to examine static and dynamic postural stability. These tests range from generic screenings of balance in functional contexts via performance-based tests to highly sensitive three-dimensional kinematic and kinetic motion analyses. Latter biomechanical approaches are applied in this thesis and will be described as far as relevant in the subsequent sections.

Posturographic measurements for the investigation of static stability

As mentioned previously, to ensure stability under static conditions, the postural control system aims to maintain the CoM within the boundaries of the BoS. However, computation of the CoM and the BoS is associated with considerable methodological effort. Therefore, the indirect method of *posturography* has been established as the method of choice for studying static stability (Duarte et al., 2011).

The principle of posturographic measurements is based on Newton's third law of motion and the assumption that while quiet standing, the body behaves like an inverted pendulum and the only possibility to interact with the environment – and by this means to passively move the CoM – is to apply forces to the supporting surface. These forces are opposed by the ground reaction force, which is the resultant force vector that is numerically and physically equivalent to all the applied forces and pushes against the parts of the body that are in contact with the ground. This ground reaction force can be measured over time by means of force plates, which are typically equipped with four three-dimensional force transducers, one in each corner of the plate. The location of the resultant force vector on the ground, which results from the distribution of the forces to the area of contact, is called the center of pressure (CoP) (Robertson et al., 2004).

The CoP is an indirect measure of postural sway and has been used to characterize the quality of the postural control system during quiet stance. Studies simultaneously recording the motions of the CoM and the CoP showed that the CoP moves continuously around the CoM to keep the latter within the BoS (Figure 2.1) (e.g., Winter, 1995; Sturnieks & Lord, 2008; Duarte et al., 2011). As the difference between the CoP and CoM is highly correlated with horizontal accelerations of the CoM, changes in CoP displacements will indirectly reflect alterations in CoM displacements (Winter et al., 1998). Hence, computation of the CoP over time in various disciplines has been considered an easily accessible but profound insight into the neuromechanics of static postural control (Winter et al., 1990).

Standardization is an indispensable prerequisite for the investigation of static stability and the identification of potential deficiencies. Recommendations include, among others, test instructions, test durations, number of trial recordings, and test circumstances such as illumination, noise, room size and usage of visual cues. Further concrete advices relate to the sampling rate, data processing and the variables for estimation of static stability such as the breakdown of the CoP signal into anteroposterior and mediolateral components (e.g., Kapteyn et al., 1983; Kirby et al., 1987; Mouzat et al., 2004; Scoppa et al., 2013).

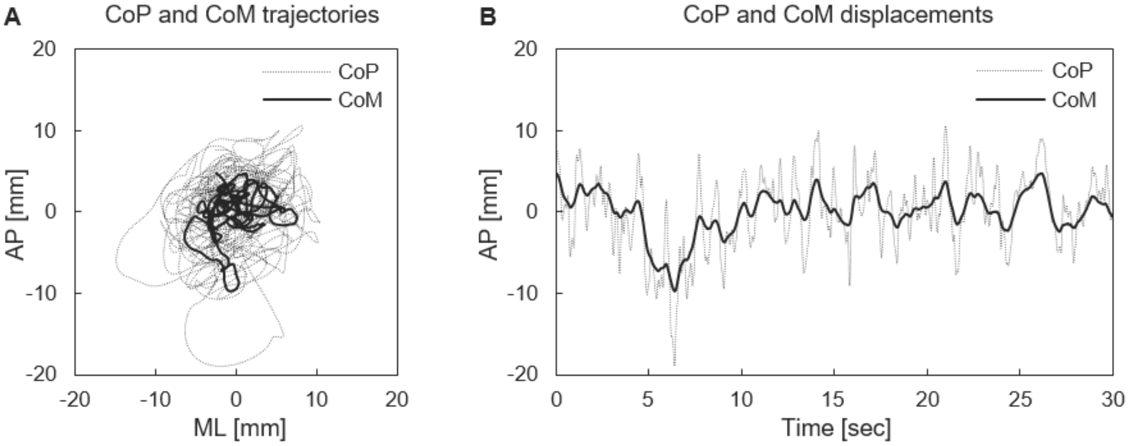


Figure 2.1 Simultaneous recording of center of mass (CoM) and center of pressure (CoP) displacements during a 30-sec single-leg stance. CoP excursions have a higher frequency and amplitude, and oscillate either side of the CoM. **A**, trajectories of CoP and CoM in anteroposterior (AP) and mediolateral (ML) directions; **B**, time domain of CoP and CoM displacements in AP direction.

With regard to the measures of static stability, most researchers traditionally refer to the spatial and temporal features of the trajectory of the CoP. Although these measures are not undisputed, they have been proven to enable reliable and valid assessments of static postural sway (Vuillerme et al., 2008; Pinsault & Vuillerme, 2009; Bauer et al., 2010; Ruhe et al., 2010). The extent of postural sway, characterized by the CoP path length over time, is believed to reflect the acute demand for neuromuscular control of balance (Clark & Riley, 2007). The area of the 95% confidence ellipse of the CoP is a measure of the spatial variability of postural sway. Similar to the margin of stability, which is determined by how close the CoP is to the boundary of the BoS, it is thought to indicate the postural instability of a given subject (Vuillerme et al., 2008; Macpherson & Horak, 2013). Others researches have suggested that characterizing the relationship between the CoM and the CoP in terms of a scalar distance, representing the error signal to be used by the postural control system, provides a better estimate of the efficiency of postural control than either CoP or CoM alone (Corriveau et al., 2001; Shumway-Cook & Woollacott, 2007). Furthermore, up-to-date approaches utilize measures like the sample entropy or mean power frequency to investigate specific patterns of postural sway, aiming to identify the underlying characteristics of neuromuscular control (Ruhe et al., 2010; Saripalle et al., 2014).

Simulated forward falls for the investigation of dynamic stability

Due to the fact that fall-related events mostly occur during locomotion such as tripping or slipping while walking (Blake et al., 1988), measurements of dynamic stability have become a particular issue of concern and a useful experimental approach for understanding the neural control of balance under dynamic conditions (Maki et al., 1994; Horak et al., 1997). Whereas some paradigms have been developed to investigate postural responses to sudden external perturbations while standing or walking (e.g., Maki et al., 1994; Henry et al., 1998), others estimated the time to stabilization after drop landings or perturbations of unstable surfaces (e.g., Fransz et al., 2014; Giboin et al., 2015; Holden et al., 2016).

Do et al. (1982) introduced an experimental paradigm for the investigation of balance recovery after forward loss of balance, simulating the process of forward falling as it is might be induced by tripping while walking. Within this test, subjects are encouraged to recover balance by taking a rapid single step after being suddenly released from an inclined forward posture (Figure 2.2 A) (Wojcik et al., 2001; Karamanidis et al., 2008). The quantification of dynamic postural stability refers to the inverted pendulum model of balance and the assumption that a great margin of stability (MoS) aids to recover balance (Winter et al., 1998). The MoS is computed based on the extrapolated CoM concept (Hof et al., 2005). Herein, the extrapolated CoM ($xCoM$) is calculated as follows:

$$xCoM = pCoM + \frac{vCoM}{\sqrt{g/l}}$$

where $pCoM$ is the projection of the anteroposterior position of the CoM on the ground, $vCoM$ is the anteroposterior velocity of the CoM, g is the acceleration of gravity, and l is the distance between the CoM and the center of the ankle joint in the sagittal plane (Hof, 2008). Ultimately, the MoS in anteroposterior direction is determined as follows:

$$MoS = pBoS - \ xCoM$$

where $xCoM$ is the anteroposterior component of the extrapolated CoM, and $pBoS$ is the anterior boundary of the BoS, which is the projection of the anteroposterior position of the toe of the recovery limb on the ground.

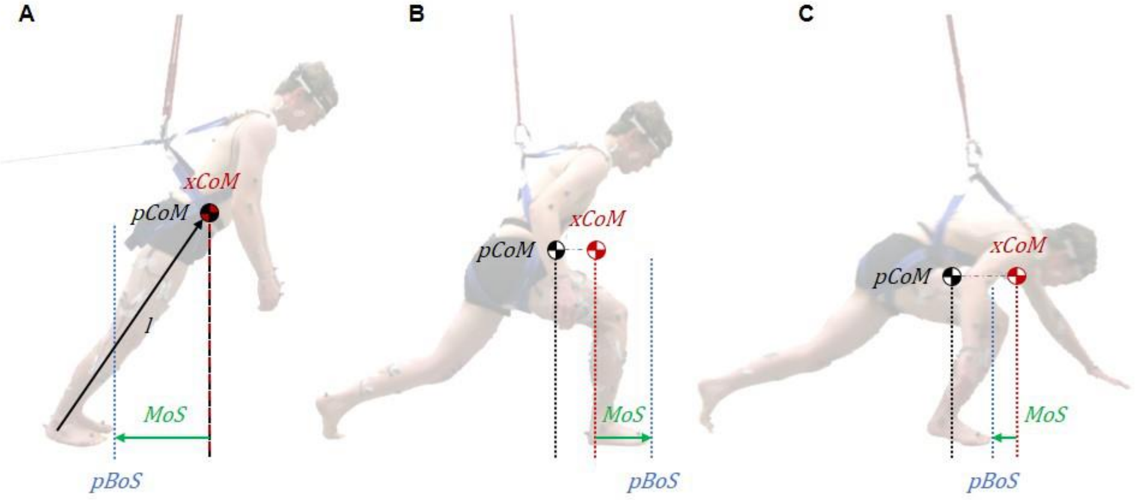


Figure 2.2 Analysis of dynamic stability after forward loss of balance. Anteroposterior positions of the center of mass (CoM), extrapolated center of mass (xCoM), and the anterior boundary of the base of support (pBoS). The margin of stability (MoS) refers to the relative position of the xCoM with respect to the pBoS. Stability is maintained when the MoS shows positive values (arrow to the right), whereas a loss of stability is indicated by negative values (arrow to the left). **A**, initial forward-inclined position, whereat stability is guaranteed by the horizontal cable attached to the safety harness worn by the subject. **B**, successful balance recovery. **C**, unsuccessful balance recovery.

The extrapolated CoM concept suggests that postural stability is maintained when the projection of the extrapolated CoM is located within the BoS, i.e., the MoS shows positive values (Figure 2.2 B) (Hof et al., 2005; Karamanidis et al., 2008). A loss of dynamic stability, in turn, is indicated by negative values of the MoS, i.e., in cases where the extrapolated CoM exceeds the anterior boundary of the BoS (Figure 2.2 C).

The above-depicted paradigm of simulated forward falls along with the extrapolated CoM concept has been shown to evince postural deficits in diverse populations and is still frequently used in clinical and scientifical settings (Wojcik et al., 2001; Karamanidis & Arampatzis, 2007; Arampatzis et al., 2008; Karamanidis et al., 2008; Curtze et al., 2010; Barrett et al., 2012; Carty et al., 2012; Cheng et al., 2014; Graham et al., 2014).

2.2 Sensorimotor process for balance control

The control of balance is not regulated by a single system but emerges from a complex interaction among diverse bodily systems that work cooperatively to maintain stability of the body. The organization of these systems is determined by the functional task and environmental constraints (Shumway-Cook & Woollacott, 2016).

Formerly, it was believed that balance is automatically controlled by distinct preprogrammed activation patterns, forming a set of reflex-like responses that are elicited in a task-specific manner by stimuli to particular sensory systems (Taube et al., 2009). In view of the manifold types of stimuli and the plethora of postural responses, it is however unlikely that such automatic postural responses are preprogrammed in the CNS (Schmidt & Lee, 2011). More recent studies on postural responses have helped leading the way from a reflex-concept of postural control to a kind of systems approach, which emphasizes an adaptive goal-directed organization of multiple interacting systems that is centrally organized based on prior experience and intention (Horak et al., 1997). Consequently, postural control is considered a dynamic interaction involving the coordination of sensory and motor strategies that are actively processed and that the nervous system learns to accomplish (Horak, 2009). This neural control operates at a semi-automatic level, wherein the nervous system employs a flexible continuum of muscle activation patterns that are responsible for the specific postural adjustments (Shumway-Cook & Woollacott, 2007; Macpherson & Horak, 2013).

Yet regardless of the task-specific demands, maintaining and restoring balance emerges from the complex system of sensorimotor mechanisms, involving multisensory inputs and billions of neurons in different parts of the brain that coordinate hundreds of muscles to control a plenty of joints with its several degrees of freedom (Rosenbaum, 2010). Postural stability in this context is not a specific position but rather a dynamic process dealing with the manifold problem of redundancy, which is further aggravated by task constraints as, e.g., the availability of sensory information, the size of the BoS or the presence of internal or external forces (Horak, 2006). Therefore, the nervous system is required to detect or predict postural instability, and thereupon to produce appropriate muscle forces that complement and coordinate with all the other forces so that the body CoM is well controlled and balance is maintained (Horak et al., 1997).

2.2.1 Sensory integration

The sensory input, which the postural control systems uses to identify or predict postural sway, is primarily derived from the visual, vestibular and somatosensory receptors. Vision supplies feedback about the external environment and the position and movements of the body relative to the surrounding. The vestibular system, located in the inner ear, is important for the perception of self- and head-motion and provides vital information for neuromotor control of upright posture and for the coordination of head, eye and body movements (Brandt & Dieterich, 1999; Day & Fitzpatrick, 2005; Cullen, 2012; Dieterich & Brandt, 2015). Somatosensory input comprises peripheral feedback arising within the body, including proprioception and tactile sensation. Proprioception derives from receptors in muscles, tendons and joints mediating sensations regarding body position and movement, particularly muscle tension and length, as well as joint position, stress and motion. Tactile sensation refers to the awareness of touch and derives from receptors in the skin sensitive to pressure (Sturnieks & Lord, 2008; Shumway-Cook & Woollacott, 2011; Macpherson & Horak, 2013).

In quiet standing, somatosensory sensation is evidenced to be the most important sensory system in the regulation of balance (Horak et al., 1990; Fitzpatrick et al., 1994; Taube et al., 2009). For healthy subjects balancing on a firm BoS in a well-lit environment, Peterka & Loughlin (2004) estimated the contribution of the somatosensory system to 70%, and those of the vestibular and visual systems to 20 and 10%, respectively. This distribution is known to change as a function of task constraints, especially under dynamic conditions. Besides, balance can still be maintained even though all sensations are not fully available, e.g., as a result of sensory impairments (Horak et al., 1990; Hamacher et al., 2016). However, since human balance control relies on three separate sensory systems, there is a certain degree of redundancy, which can be put into use if one or more of the systems is temporally or permanently lost (Winter, 1995). For instance, the vestibular system has strong reciprocal inhibitory connections with the visual system, which therefore can compensate for declines of visual processing capabilities (Brandt & Dieterich, 1999; Faraldo-Garcia et al., 2012). The extent to which one sensory input can compensate for the loss of another remains unclear, however (Fitzpatrick et al., 1994; Sturnieks & Lord, 2008).

Essentially, to maintain or recover balance, all sensory information has to be processed in parallel in order to adequately adjust the motor commands. To do so, the information sensed by the various receptors is transmitted continuously via afferent nerve pathways to the different areas of the central nervous system (CNS). Herein, the input is rapidly processed to provide a coherent picture of the position and motion of the body in space (Macpherson & Horak, 2013). It is of particular notice, that the different sensory information is not processed separately but is rather integrated and relatively re-weighted depending on the objectives of the task and the environmental constraints (Horak, 2009; Taube et al., 2009). This multisensory integration is known to produce a more robust and reliable representation of one’s environment that ultimately can make a stimulus more salient (Hong & Shim, 2016).

2.2.2 Neural control

As described previously, postural responses traditionally were considered a summation of reflexes reactively controlled via the spinal cord (Horak et al., 1997). Nowadays, neural control of balance is proposed to be an active process, whereby multi-sensory information act on various sites in the CNS so that an adaptable postural control can be achieved (Takakusaki, 2017). Besides the spinal cord, different areas of the brain including the brainstem, cerebellum, basal ganglia and motor cortex are involved in the neuronal control process (Papegaaij & Hortobágyi, 2017).

Indirect evidence on a cortical participation comes from research employing the *dual-task paradigm*. Asking the participants to perform a postural control task and a cognitive task together, several studies have shown that even the regulation of quiet standing requires some kind of attentional demands. This demand is indicated by decreased performance on either one or both tasks as an index of the extent of attentional shared resources (for review, see Woollacott & Shumway-Cook, 2002). For simple postural tasks such as sitting or standing attentional demands are rather low. However, the allocation of attentional resources increases when subjects are exposed to dynamic conditions or if the availability of sensory information is decreased (Lajoie et al., 1993; Teasdale et al., 1993; Rankin et al., 2000; Woollacott & Shumway-Cook, 2002; Reilly et al., 2008).

Searching for the entirety of structure involved in postural control process, yet wide parts of the CNS have been identified as being crucial. The quickest and simplest, but also most unspecific processing of afferent information, takes place on the spinal cord level. For instance, a rapid elongation of calf muscle spindles triggers a monosynaptic stretch reflex that occurs within 40 to 50 ms (Gollhofer & Rapp, 1993). These non-voluntary reflexes contribute only little functional torque to correct postural equilibrium. Therefore, higher centers of the CNS can modulate the spinal excitability. Particularly in challenging postural situations, the reflex amplitude can be reduced by increasing the presynaptic inhibition (Llewellyn et al., 1990; Hoffman & Koceja, 1995; Meunier & Pierrot-Deseilligny, 1998; Taube et al., 2009). In turn, these rapid but unspecific postural responses via reflexes are suppressed and sensorimotor afferences run via ascending pathways to the supraspinal structures.

The sensory signals flowing into the supraspinal structures initially converge to the brainstem and cerebellum as well as to the visual, vestibular and primary sensory cortices. Herein, the sensations are integrated and an internal representation of the body and its surrounding is constructed. At the supplementary and premotor areas, these information are then utilized to select and to produce, in close cooperation with the cerebellum and the basal ganglia, the appropriate motor programs (Takakusaki, 2017). Whereas the cerebellum is mainly concerned with assigning the correct postural responses to the specific situation (Nashner, 1976) and to coordinate the activity of the involved muscles (Diener & Dichgans, 1992), the basal ganglia enable control of sensorimotor integration and continuous adjustment of posture and balance relative to the changing environmental conditions (Visser & Bloem, 2005). Input from the prefrontal cortex finally triggers to run the constructed motor programs and adequate responses can be achieved (Takakusaki et al., 2016). Ultimately, inside the cerebral cortex a widespread network of structures appears to be crucial for the processing of multisensory information and the selection and initiation of appropriate motor programs (Dieterich & Brandt, 2008; Taube et al., 2015; Cioncoloni et al., 2016).

The responsibilities of the different parts of the CNS are well-known to change depending on the specificity of the task (Taube et al., 2009). In normal and predictable conditions, motor commands primarily take place at lower spinal levels with neural circuitry tuned by self-organized processes and local loops of assistance, operating at an automatic non-voluntary level (Lajoie et al., 1993). This automatic process of postural control mainly is mediated by the descending pathways from the brainstem (Takakusaki et al., 2016). Herein, specifically the formatio reticularis has been assigned a major function in the regulation of postural muscle tone and basic postural reflexes. On the other hand, balancing in unfamiliar circumstances or exposure to external disturbances requires cognitive processing of postural control. This supraspinal involvement and increased amount of cortical influence is necessary to perform movements adapted to the environment (Lajoie et al., 1993).

The basal ganglia and the cerebellum are suggested to be the key areas of the postural control system (Taube et al., 2009; Takakusaki et al., 2016). They possess reciprocal connections with the brainstem and the cerebral cortex and may therefore affect both the automatic and cognitive processes of balance control. Nonetheless, studies using transcranial magnet stimulation (TMS) have found enhanced excitability of the motor cortex even during fairly simple tasks like unperturbed standing or walking (for review, see Jacobs & Horak, 2007). Recently, Herold et al. (2017) reinforced the important role of sensorimotor cortical areas for balance control, particularly of supplementary motor area in online control of postural sway. Therefore, it has been suggested that even highly automatized movements partly rely on cortical input, either in terms of a standby modus or by activating or coordinating the subcortical structures (Taube et al., 2009).

The individual contributions of the different structures of the CNS have further been shown to change following balance training (Beck et al., 2007; Taube et al., 2008; Taube, 2013). While untrained subjects mainly rely on spinal and cortical contributions exaggerating or retarding postural responses, in experts spinal and cortical excitability were found to be decreased (Taube et al., 2009). Hence, improved postural stability was deduced from enhanced participation of subcortical structures. Particularly, cerebellum and basal ganglia become increasingly important as the simplicity and automation of postural responses increase (Balasubramaniam & Wing, 2002; Jahn et al., 2004; Ferraye et al., 2014). This assumption is supported by a number of studies that have demonstrated structural changes in above-mentioned areas in response to challenging whole-body balance training (Taube et al., 2008; Taubert et al., 2016). Nonetheless, the exact contribution of subcortical and cortical areas to neuromotor control of balance yet remains to be clarified.

2.2.3 Postural responses

After central processing, the motor commands arising from lower and higher neural centers travel along the corticospinal tract to the α motor neurons, activating the targeted muscle groups to exert the appropriate torques returning the human body to equilibrium (Taube et al., 2009). In quiet stance, some stability to maintain postural orientation and balance is supplied passively by the musculoskeletal system, particularly through soft tissues and bone-on-bone forces. Besides, tonic postural muscle activity provides antigravity support and flexibly adjusts to changes in support and environmental conditions (Gurfinkel et al., 2006). However, stiffening the entire body through muscle co-contractions is not sufficient to maintain balance. Yet, humans even during quiet stance continuously require small but complex patterns of corrective muscle activation to produce specific forces to control the body's CoM (Macpherson & Horak, 2013). These postural responses are mainly shaped by the sensory characteristics of the perturbation. Nevertheless, it is important to note that they are not purely reactive but may also act in a proactive manner. In particular, CNS mechanisms relating to the individual's expectations, intentions, and prior experiences do largely influence the generation of appropriate motor responses (Horak, 2006). Studies on how humans control balance against these internal or environmental disturbances have led to two concepts of postural responses: *anticipatory* and *compensatory postural adjustments*.

Anticipatory postural adjustments

Anticipatory postural adjustments (APA) circumscribe postural responses that in a proactive manner compensate for voluntary movements as well as for external perturbations predictable to the affected person. Although both situations can destabilize postural orientation and balance, the CNS has advance knowledge of the upcoming effects and activates these APA, often prior to the primary movement, to counter the postural destabilization associated with the forthcoming movement (Macpherson & Horak, 2013). These motor programs are selected and programmed in the motor cortical areas, running to the distal muscles to execute postural adjustments that are optimal for achieving goal-directed movements (Takakusaki, 2017). Hence, APA are activated within a feedforward control scheme prior to any sensory feedback indicating instability. They are based to a large extent on experience and the exact prediction of the postural requirements (Horak, 2009). Apart from the motor cortical areas, the cerebellum and visual perception of environmental surroundings have been attributed to play a central role in this process (Ramnani, 2006). Although APA are very specific to the biomechanical conditions, there seems to be a central set of preselected postural muscle synergies. These muscle synergies encompass leg and trunk muscle co-activations along with muscle activities in the body segments mostly affected by the forthcoming movements or external forces.

Compensatory postural adjustments

Compensatory postural adjustments (CPA), also referred to as automatic postural responses, comprise feedback-driven motor reactions that deal with the disturbance itself. Albeit postural responses can also appear in form of spinal reflexes or voluntary reactions, they primarily follow an automatic non-voluntary control by the brainstem, cerebellum and basal ganglia (Horak, 2009). These long-loop reflexes ensure an increased precision of postural responses compared with spinal reflexes, but at the same time are accompanied by increased response latencies. CPA are commonly triggered at 100 ms in response to the perturbation, which is faster than voluntary reactions but slower than stretch reflexes (Horak, 2009; Taube et al., 2009). Compared to stretch reflexes, CPA comprise synergistic activations of muscle groups in stereotyped characteristic sequences (Macpherson & Horak, 2013). They may also include responses in muscles far from the site of perturbation (Ting & Macpherson, 2005). As will be discussed in greater detail hereinafter, the recruitment of muscles follows a central set of muscle synergies that are specific to the initial conditions and adapt to prior experience and expectations (Horak, 2009).

In essence, higher level neurological processes enable anticipatory mechanisms to protect against imbalance and subcortical areas trigger adaptive compensatory mechanisms for the ability to react to changing demands of the particular task (Sturnieks & Lord, 2008).

2.2.4 Postural strategies

Even though body sway includes control of multiple segments, human balance control is often simplified and modeled as an inverted pendulum biomechanical system. Herein, the

CoM is located at the upper end of a (semi-)rigid link that pivots about a joint at the base, i.e., the ankle joint (Winter, 1995). From this biomechanical perspective, two main strategies have been proposed of how the nervous systems returns balance after perturbation – one that maintains the CoM over the BoS (*fixed-support*) and another that changes the BoS to capture the CoM (*change-in-support*).

Fixed-support strategy

The fixed-support strategy forms a continuum from the ankle to the hip strategy (Horak, 2009). The ankle strategy typically applies in quiet stance and is appropriate for small amounts of postural sway, especially for ensuring balance in anteroposterior direction. This strategy predicts that ankle plantar and dorsi flexors alone act to control balance, suggesting the body to resemble a single segment rotating about the subtalar joint (Figure 2.3 A) (Horak & Nashner, 1986; Winter, 1995).

However, if perturbations increase, the ankle strategy cannot account for adequate postural responses in anteroposterior directions. Then, the hip strategy must be employed to optimize neuronal effort. Specifically, when the CoM must be moved more quickly – such as for faster or larger perturbations – or when standing on surfaces not allowing ankle muscles to act – for instance because the feet are placed sideways on a narrow beam – the hip strategy is used to move the CoM anteriorly and posteriorly (Winter, 1995; Balasubramaniam & Wing, 2002; Horak, 2009). Likewise, the hip strategy generally is applied for mediolateral neuromuscular control in side-by-side standing, using load/unload mechanism by the hip abductors and adductors to shift the CoM laterally (Winter et al., 1996). In the hip strategy, the body resembles a two-segment inverted pendulum system, whereat the total body pivots about the supporting subtalar joint and the upper body additionally pivots about the hip joint (Figure 2.3 B) (MacKinnon & Winter, 1993).

Both strategies may work separately, but their roles can also reverse in other standing positions and may adapt gradually depending upon the central set of prior conditions (Winter, 1995; Horak, 2009). Furthermore, it has been shown that sensory information play an important role in the selection of postural strategies. Whereas vestibular information is necessary to control balance in tasks requiring the use of the hip strategy, somatosensory information predominates for tasks involving the ankle strategy (Horak et al., 1990). Research investigating whether knee motions could contribute to feet-in-place balance recovery suggests that performance is better without knee motions, confirming the advantage of having only ankle and hip strategies (Cheng, 2016).

Change-in-support strategy

Although the change-in-support strategy also pertains to conditions, in which it is not important to keep the feet in place, this strategy primarily comes into effect when fixed-support strategies are insufficient to recover balance (Maki & McIlroy, 1997; Horak, 2009). Commonly, this strategy follows extensive perturbations that force subjects to enlarge their BoS by taking a step to decelerate the body's motion (Figure 2.3 C). If railing or other objects are available, balance can also be restored by using arm support. Such reaching reactions incidentally are even faster than stepping reactions (McIlroy & Maki, 1995), which is of great significance as the success of capturing the CoM ultimately depends on the latency and adequacy of postural responses.

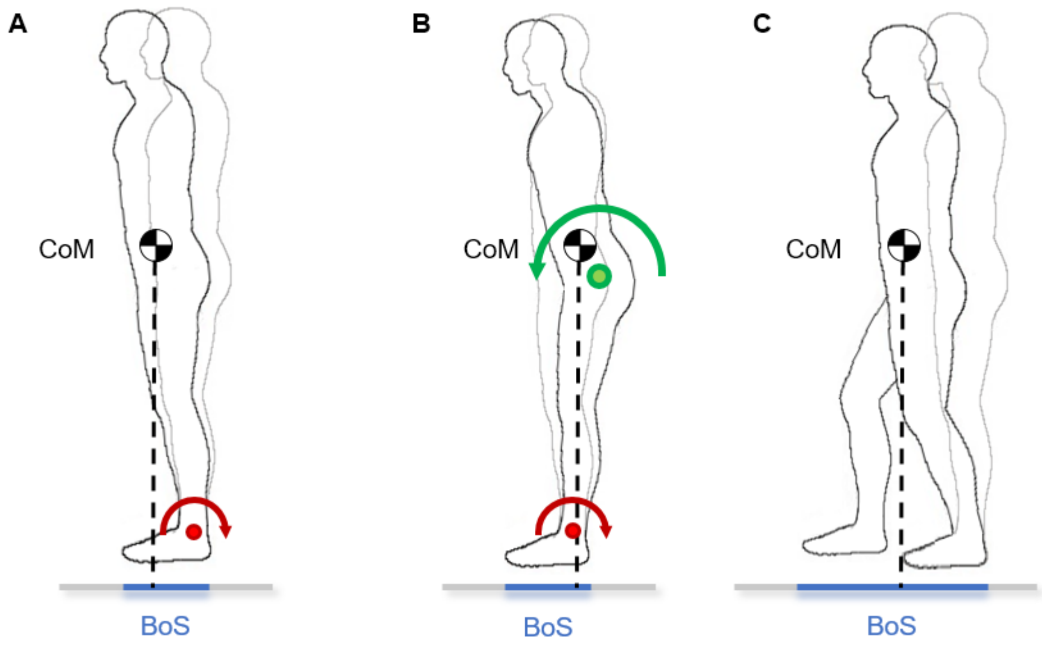


Figure 2.3 Postural strategies of balance control used to maintain the center of mass (CoM) over the base of support (BoS) or to capture the CoM by enlarging the BoS. **A**, ankle strategy; **B**, hip strategy; **C**, stepping strategy.

2.2.5 Postural synergies

Individual postural muscles have unique directional tuning curves. As such, each muscle has stereotypical directional characteristics, responding to a limited set of sway directions (Macpherson & Horak, 2013). By creating a flexible continuum of multi-muscle postural synergies, the nervous system eliminates the need to control each muscle individually and therewith simplifies the selection and coordination of multiple muscles (Henry et al., 1998; Krishnamoorthy et al., 2004; Horak, 2009). Hence, groups of postural muscles are co-activated in synergies, and the muscles within a synergy receive common motor commands, which in turn are used to implement the different postural strategies. In this way, the many muscles are controlled by just a few signals, reducing the time needed to generate the appropriate postural responses (Macpherson & Horak, 2013). Each muscle synergy specifies how a particular muscle is activated together with the others. Nonetheless, each muscle may belong to more than just one synergy, and it is not always the same muscles that are recruited together (Macpherson & Horak, 2013).

The set of muscles recruited in postural responses is modifiable in a task-dependent manner, which largely depends on the initial conditions. For quiet standing on stable support surfaces, uncontrolled manifold (UCM) analysis has resulted in the detection of only three major functional muscle groups, named M modes, that are needed to account for the activation patterns of eleven postural muscles (Krishnamoorthy et al., 2003). Furthermore, it was shown that a set of five M modes, including both reciprocal and co-contraction M modes, preserves stability when exposed to surface instability and grasping a stable support is available (Krishnamoorthy et al., 2004). However, the composition within and between these M modes may change. Even though upright stance is provided by a small set of muscles, the synergies established during bipedal stance are different from those utilized during single-leg stance (García-Massó et al., 2016). Conversely, when grasping a stable object, co-contraction M modes uniting hip and shoulder muscles predominate (Krishnamoorthy et al., 2004). Hence, muscle synergies formed by the CNS are modifiable in a task-specific manner, enabling adaptation to different environmental conditions, whereby postural muscles are recruited only when actually needed (Danna-Dos-Santos et al., 2008; Danna-Dos-Santos et al., 2009; Macpherson & Horak, 2013).

Postural synergies are also modifiable in a time-dependent manner. After surface translations or rotations in free stance, the responses typically radiate from plantar and dorsi flexors towards knee, hip and trunk muscles (Winter, 1995). In contrast, when holding onto a stable support, leg muscles initially are suppressed and arm muscles are activated to counteract the perturbations (Cordo & Nashner, 1982). Obviously, the CNS recognizes the need to address the most relevant muscle groups and the joints closest to the perturbation first (Winter, 1995). To optimize the response for the particular conditions, postural synergies are well-described to also adapt with repeated trials of perturbation (Horak & Nashner, 1986). Because postural responses are largely influenced by recent experience, the adaptation occurs only gradually, especially when subsequent tasks involve different postural strategies (Macpherson & Horak, 2013).

2.3 Influencing factors

Given the multiplicity of systems and structures involved in the postural control process, a multitude of internal factors may impair postural stability and therewith increase the likelihood of falls. For instance, any type of deterioration of the underlying postural systems, such as experimental modulation or pathologic loss of sensory functions (e.g., Horak, 2006; van Dieën et al., 2015; Cofré Lizama et al., 2016), or damage to central cognitive functions and structures (e.g., Lisberger & Thach, 2013; Takakusaki et al., 2016), may disturb appropriate balance control and result in falling. Similarly, declines in central processing and motor systems induced through cognitive interference (e.g., Rankin et al., 2000; Patel & Bhatt, 2015; Lajoie et al., 2016), muscle fatigue (e.g., Corbeil et al., 2003; Vuillerme et al., 2009; Singh & Latash, 2011; Paillard, 2012; Monjo et al., 2015), injuries and acute or chronic pain (e.g., Boudreau & Falla, 2014; Quek et al., 2014; Hatton et al., 2015) are known to induce significant and context-specific balance and gait disturbances. Further factors with the potential to impair balance include, among others, time-of-day (e.g., Heinbaugh et al., 2015), body weight (e.g., Simoneau & Teasdale, 2015), physical activity (e.g., Kiers et al., 2013), muscle power and force potential of lower limbs (e.g., Karamanidis et al., 2008; Han & Yang, 2015).

In most cases, the reason for sustaining falls is a general decline in sensorimotor function, such as during childhood and advanced age. Postural control undergoes fundamental developments during the lifespan (Granacher et al., 2011a). It is well accepted that it needs approximately one year to see infants to stand upright on their own and to take the first steps. With the progress of infant development, a continuous decrease of postural sway during unperturbed stance can be found. However, it is not until the age of seven years that children are able to balance as effectively as adults (Riach & Hayes, 1987). Although immaturity of the sensory systems would seem a logical explanation, the visual and vestibular systems are largely mature well before balance performance is adult-like (Dayal et al., 1973; Neuringer & Jeffrey, 2003). It is more likely that differences in postural control between children and adults are due to insufficient integration of multiple sensory input and difficulties to resolve sensory conflicts (Peterson et al., 2006). In fact, it takes up to twelve years of age until adult-like use of sensory information – especially visual and vestibular information – and well-organized muscular responses to perturbation – as evident by mature control strategies and synergies – begin to appear (Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985; Peterka & Black, 1990; Peterson et al., 2006).

A similar but inverse progress can be observed in the elderly. With increasing age there is a progressive loss of functioning of sensory, motor and central processing systems (Taube et al., 2009; Granacher et al., 2011b; Muehlbauer et al., 2015). Desensitization of muscle spindles, declines in the number of sensory and motor neurons, atrophy of axons, reductions in nerve conduction velocity and decreased muscle strength are some of the factors frequently discussed to account for the loss of full neuromuscular functionality (for review, see Granacher et al., 2011b; Muehlbauer et al., 2015). Furthermore, there is an age-related reorganization of neural control, with increased cortical activation and decreased intracortical inhibition, which becomes even more prominent when postural task difficulty increases (Papegaaij & Hortobágyi, 2017). Experiments under dual-task conditions support these findings, documenting a decrease in postural control with progression of concurrent cognitive or motor task complexity (for review, see Woollacott & Shumway-Cook, 2002). This indicates that decreases in postural control while concurrently being engaged in attention-demanding tasks are probably due to age-related deteriorations in central information processing capacities.

Taken together, the diverse changes in overall sensory and motor functions related to postural control dramatically increase the likelihood of falls, specifically in infants and the elderly. Besides, there are also psychological factors that are associated with a greater risk of falling, including mood state, depression, restrictions in activities of daily living, fear of falling and a history of falls (Lord et al., 1994; Bolmont et al., 2002; Era et al., 2006; Sturnieks & Lord, 2008; Kiers et al., 2013). In addition to the commonly researched and well-known influential factors indicated above, in recent decades several studies have suggested a potential impact of the craniomandibular system on human postural control. This issue has become a controversial topic in research, not only in dentistry but also in adjacent fields such as human movement science and neuroscience (Manfredini et al., 2012).

2.4 Craniomandibular system and human postural control

The craniomandibular system (CMS) is a functional unit comprising the plethora of soft and hard tissues surrounding the mouth and jaws, encompassing, e.g., the dental arches, the skeletal components (maxilla and mandible), the temporomandibular joint, the masticatory muscles as well as the nervous and vascular supplies (Cuccia & Caradonna, 2009). These structures primarily allow masticatory functions such as biting and chewing, but also enable functions as swallowing or speaking (The Academy of Prosthodontics, 1999). The muscle producing the most significant forces during mastication is the masseter muscle. Along with the other muscles of mastication, the masseter is innervated by the mandibular nerve. The mandibular nerve is one of three branches of the trigeminal nerve. Besides its motor function, the trigeminal nerve provides tactile, proprioceptive and nociceptive sensations of the face, chin, and jaw, including masticatory muscles and periodontal ligaments. The innervations of the CMS enter the brainstem at the level of the pons and are then reflected in the motor and sensory areas of the cerebral cortex (Dessem & Taylor, 1989; Nakahara et al., 2004; Cuccia & Caradonna, 2009).

2.4.1 Neuroanatomical connections

Albeit the functional interrelation of the CMS with remote body regions is still disputed and the concepts discussing the underlying mechanisms are manifold, the trigeminal nerve commonly is proposed to play a key role regarding a potential association of the CMS with the human postural control system. The assumption of reciprocal influences arose from early animal studies, in which trigeminal projections to all levels of the spinal cord have been shown (Walker, 1939; Kuypers & Maisky, 1975; Ruggiero et al., 1981). Later animal studies documented that the trigeminal nerve also maintains anatomical connections with nervous structures that are involved in the postural control process (Buisseret-Delmas & Buisseret, 1990; Marfurt & Rajchert, 1991; Billig et al., 1995; Buisseret-Delmas et al., 1999; Pinganaud et al., 1999). More precisely, the authors found afferent somatosensory signals from facial receptors to be directly transmitted to widespread and functionally heterogeneous areas of the CNS, including the brainstem, vestibular nuclei, the reticular formation and the cerebellum. By this means, structures strongly associated with postural control may receive direct afferent information from the CMS – in addition to those reported for the neck and body (Lisberger & Thach, 2013).

2.4.2 Neurophysiologic phenomena and biomechanical couplings

Whereas the integration of the CMS into the postural control system has been proven anatomically only in animals, few human studies reinforce this integration on a neurophysiological basis. Deriu et al. (2003) recorded EMG responses in active masseter muscles following an electrical vestibular stimulation, indicating that the stimulation evoked a short latency vestibulo-masseteric reflex, which amplitude was linearly related to the stimulation intensity. Vice versa, researchers noticed trigeminal modulation of auditory and vestibular symptoms as well as of cervical reflexes in the cat (Abrahams et al., 1993; Vass et al., 1998; Marano et al., 2005). Based on these findings, it has been suggested that spinal trigeminal nuclei are to some extent involved in the modulation of sensory input arriving at the CNS and by this means influence the coordination of postural movements (Ruggiero et al., 1981; Devoize et al., 2010).

Further studies have been focusing on biomechanical couplings of the CMS with other body segments. Herein, maximal jaw opening-closing activities have been shown to be accompanied by coordinated head and neck movements (Yamabe et al., 1999; Eriksson et al., 2000; Haggman-Henrikson & Eriksson, 2004), supposedly caused by co-contractions of jaw and neck muscles (Ehrlich et al., 1999; Shimazaki et al., 2006; Hellmann et al., 2012; Giannakopoulos et al., 2013a; Giannakopoulos et al., 2013b). Interestingly, the start of the head movements proceeded the start of the mandibular movements, supporting the idea of a close functional linkage between mandibular and cranio-cervical neuromuscular systems (Eriksson et al., 2000). Anterior and posterior neck muscle co-contractions during jaw clenching incidentally are also believed to be involved in the co-existence of jaw and neck pain (Hellmann et al., 2012).

Taking all this indirect evidence into account, a functional connection between the trigeminal, vestibular and oculomotor systems could be suggested. Possibly, the entirety of sensory information delivered by all the systems is processed in tandem (Gangloff & Perrin, 2002; Cuccia & Caradonna, 2009)

2.4.3 Relation of dental occlusion and postural control

In view of the available neuroanatomical and biomechanical findings, several hypotheses addressing mutual interdependences between both systems have been postulated in recent decades (Michelotti et al., 2011). Particularly, the relation between morphologic and functional states of the CMS with whole body posture and balance have been extensively investigated. It has been suggested that changes in body posture and balance are closely linked to disorders of the CMS (Munhoz & Marques, 2009).

Clinical evidence on such interrelations comes from alterations in CMS structures brought about by acute or chronic changes in body posture (Lund et al., 1970; Tingey et al., 2001; Lippold et al., 2003; D'Attilio et al., 2004; Sakaguchi et al., 2007; Munhoz & Marques, 2009; Ohlendorf et al., 2015). Conversely, several studies have emphasized a higher frequency and an increased risk of the development of body posture alterations in subjects with diseases of the CMS (for review, see Cuccia & Caradonna, 2009; Munhoz & Marques, 2009; Manfredini et al., 2012). Primarily, temporomandibular disorders (TMD) – a group of diseases affecting the masticatory muscles, the temporomandibular joint, and the surrounding structures – have often been associated with comorbidities and chronic pain, suggesting TMD to be one of the main disorders affecting human posture (Cuccia & Caradonna, 2009; Bonato et al., 2017).

Similar correlations with impact on whole body posture and balance have been described for occlusal functions and dental malocclusions. As research demonstrates, inter alia, the loss of teeth and pathological or experimental deviation from centric relation may cause alterations of head and cervical posture as well as postural instability (Nobili & Adversi, 1996; Solow & Sonnesen, 1998; Gangloff et al., 2000; Milani et al., 2000; Bracco et al., 2004; Korbmacher et al., 2004; Sakaguchi et al., 2007; Wakano et al., 2011; Song-Yu et al., 2012). In accordance with these finding, Gangloff & Perrin (2002) have found correlations between postural control and diminishing of trigeminal afferences through unilateral anesthesia, emphasizing the potential role of trigeminal afferents in maintaining postural control.

However, although evidence continues to accumulate, the issue of occlusal and postural correlations is still discussed controversially (Treffel et al., 2016). The reason for this is twofold. First, the available literature provides inconsistent results. In particular, several studies failed to prove any association at posturography level, either in healthy subjects or in subjects with malocclusion or TMD (for review, see Cuccia & Caradonna, 2009; Michelotti et al., 2011; Manfredini et al., 2012). Besides, disorders of the CMS and human posture were shown to also exist entirely independent of each other, suggesting functional but no pathophysiological or cause-effect relations (Manfredini et al., 2012; Silvestrini-Biavati et al., 2013). Secondly, the prevailing uncertainty is underpinned by the fact that many studies suffer from major deficiencies. As stated in three recent reviews, these deficiencies primarily relate to weak experimental designs, including non-representative populations, to the absence of control groups and to the adoption of measurement methods the validity of which is not given (Cuccia & Caradonna, 2009; Michelotti et al., 2011; Manfredini et al., 2012). Further methodological issues are the diversity of experimental conditions and the potentially affecting task instructions, which makes it considerably difficult to compare the different studies. Moreover, in most of the publications descriptions of the experimental conditions, specifically of mandibular positions during the experiments, are inadequate. This applies all the more as an international consensus about the definition of a physiological centric jaw relation is still lacking (Keshvad & Winstanley, 2000).

In conclusion, the available studies have not consistently found a predictable association between occlusal and postural features. Whereas the existence of pathophysiological and cause-effect relations between postural and craniomandibular systems may be disputed, scientific evidence to support functional connections is yet too sparse. Besides methodological issues, the controversy could also be due to the many compensations mechanisms occurring at the neuromuscular system when regulating balance (Manfredini et al., 2012). Ultimately, the current literature does not deny the existence of functional relations. Nonetheless, it would support either a low degree of correlation (Perinetti, 2006), whereby the interactions tend to disappear when descending to more caudal regions (Michelotti et al., 1999). Furthermore, it has been suggested that sensory information linked to dental occlusion comes into effect only during challenging postural tasks, and that its importance grows when other sensory cues become scarce (Tardieu et al., 2009). As dental occlusion is not the primary focus of this thesis, latter interrelations will not be discussed in any greater detail here.

2.5 Jaw clenching and human postural control

Despite the general controversy, above-introduced neuroanatomical connections have led researchers to raise questions towards the physiological significance of these relations. While much of the early research focused on jaw position and CMS disorders, recently there has been a greater interest on the effect that voluntary jaw clenching has on neuromuscular aspects of human motor control and performance. In particular, investigating the habits of jaw clenching and the mechanism accounting for potential performance enhancement have aroused considerable interest.

2.5.1 Jaw clenching and its habits

Contact between the maxillary and mandibular teeth in habitual environment is limited to the relatively brief moments of swallowing and chewing. In mandibular rest position, the teeth usually do not contact. Therefore, the sustained act of teeth clenching is thought of as parafunctional habit. However, observational studies verifying the prevalence of jaw clenching in natural environments have found teeth clenching to also occur as an unconscious habit in moments of high concentration (Okeson, 1993) or intense physical activity (Nukaga et al., 2016). Interestingly, with few exceptions clear and spontaneous masseter activity was observed during diverse actions in track and field sport athletes, predominantly in phases characterized by generation of high impulses (Nukaga et al., 2016). Taking further into account that masseter activity increases with vertical ground reaction forces during jump landing (Nakamura et al., 2016), masticatory muscle activity might be incorporated in whole body movements in terms of a non-parafunctional but physiological strategy, helping to improve systemic function. Apart from that, it appears that voluntary jaw clenching may have some benefits with regard of neurophysiologic and biomechanical performance. Latter will be elaborated shortly in the following subsections.

2.5.2 Neurophysiological effects of jaw clenching

Revolutionary work on voluntary jaw clenching and neurophysiologic performance enhancements was prepared by Erno Jendrassik in the late 19th century. The author found that clenching the teeth and pulling apart the flexed and hooked fingers amplifies the strength of lower limb reflexes in neurologically impaired patients (Jendrassik, 1885). Numerous studies confirmed the potentiating effects of this procedure, termed as the *Jendrassik maneuver*, revealing facilitation of H-reflexes and motor evoked potentials of both lower and upper limb muscles (Bussel et al., 1978; Delwaide & Toulouse, 1981; Dowman & Wolpaw, 1988; Pereon et al., 1995; Zehr & Stein, 1999; Gregory et al., 2001).

Likewise, even small muscle contractions such as jaw clenching (Miyahara et al., 1996; Takada et al., 2000; Sugawara & Kasai, 2002) or mental simulation of voluntary contractions of limb muscles (for review, see Fadiga et al., 2005) were reported to produce significant potentiation effects. Interestingly, the increase in the amplitude of the soleus H-reflex was shown to be positively correlated to the force of jaw clenching as measured by EMG activity of the masseter muscle (Miyahara et al., 1996). The even more fascinating was that this facilitation preceded the onset of masseter activity and concomitantly decreased the inhibition of reciprocal muscles (Delwaide & Toulouse, 1981; Miyahara et al., 1996; Takada et al., 2000).

In an attempt to determine the site of this remote facilitation, Tuncer et al. (2007) anesthetized the teeth of their subjects and showed that the H-reflex was facilitated the same whether the teeth were anesthetized or not. In consequence, periodontal mechanoreceptors and facial proprioceptive input were indicated to not play a major role in the facilitation process (Tuncer et al., 2007). Other studies used transcranial and brainstem magnetic stimulation to investigate if facilitation takes place on neuronal pathways at a higher level, i.e., the global corticospinal system. Showing marked facilitation of H-reflexes and motor evoked potentials, Boroojerdi et al. (2000) and Sugawara & Kasai (2002) revealed an overall enhancement in the motor system excitability, with facilitation taking place on spinal level but most likely to be of cortical origin.

2.5.3 Relation of jaw clenching and postural stability

Bearing in mind the facilitation of motor system excitability evoked by remote voluntary contractions, Takada and colleagues (2000) hypothesized that clenching the jaw might serve as a mechanism contributing to improved postural control. However, albeit researching the effect of jaw clenching is fairly simple compared to occlusal disturbances, literature concerning this topic is scarce. In fact, only few studies investigated the impact of CMS motor tasks such as chewing or jaw clenching on postural control at muscular or posturography level.

One of the difficulties in reviewing the literature is that researchers have used many conditions of clenching and different postural stability tests. In particular, most of the studies did not investigate the effects of CMS motor activities per se but rather focused on clenching in different positions or on different occlusal devices. Many publications further suffer from insufficient descriptions of the experimental design. Especially, information concerning the oral motor activity often are not adequately stated. Even when subjects were asked to clench their teeth in intercuspal or any other jaw relation, the amount of clenching as well as the task instructions mostly remain unknown (e.g., Gangloff et al., 2000; Bracco et al., 2004). Altogether, only few articles exist that at least gave information as to whether the subjects were or were not clenching their teeth during the respective experimental tasks.

The first study conducted in this context has demonstrated that, compared to a mandibular rest position, CoP sway area is not influenced by either maximal voluntary clenching in centric occlusion or maximal clenching on two cotton rolls (Ferrario et al., 1996). Likewise, centric occlusion without clenching as well as occlusion on cotton rolls without clenching had no effects on sway variables. Concerning the method and equipment applied in this study, the significance of these findings is limited, however.

Sforza et al. (2006) investigated whether maximum voluntary clenching of the jaw has different effects on postural sway when clenching is performed with or without a splint. Within this framework, clenching with the splint has been shown to have a positive effect on balance, i.e., it was contributing to decreased CoP oscillations as compared to clenching without the splint. These modifications were significantly related to increased sternocleidomastoid muscles' symmetry, evident by more symmetric EMG waves of left- and right-sided muscles. Latter findings indicates that functionally more symmetric positions of the mandible – ensured by occlusal splints – may positively affect whole body postural control (Sforza et al., 2006).

Similarly, Julià-Sánchez et al. (2015) showed that body balance on unstable surfaces is significantly better when jaw clenching is performed in cotton rolls mandibular position as compared to intercuspal position. Unfortunately, both studies did not compare the effects of jaw clenching against other oral motor tasks. This poses the critical question as to whether chewing or submaximal clench conditions could elicit similar effects.

In current literature, three studies comparatively assessed the effects of chewing on static postural stability. Therein, postural sway is reported to be significantly decreased while chewing compared to open or resting jaw positions (Goto et al., 2011; Kushiro & Goto, 2011; Alghadir et al., 2015b). Contradictory but the more interesting findings are provided by Hellmann et al. (2011c). In their study, participants were subjected to various jaw motor tasks with different control strategies, comprising unilateral chewing, maximal biting in intercuspation and on cotton rolls as well as force-controlled biting at submaximal forces of 50 to 300 N. Noteworthy, while unilateral chewing and maximal biting tasks caused no changes in CoP displacements as compared to mandibular rest positions, submaximal biting resulted in robust and significant sway reductions, seen as decreased area of the CoP confidence ellipse. This effect was similar for unilateral and bilateral submaximal biting, suggesting that contribution of occlusal proprioception is independent of the morphology of dental occlusion (Hellmann et al., 2011c; Manfredini et al., 2012). These stabilizing effects, supporting a correlation of postural balance with voluntary jaw clenching, was also confirmed by Alghadir et al. (2015a).

Apart from that, little has been reported about the effects of mastication and jaw clenching on dynamic postural stability, which is the maintenance and recovery of balance in response to internal or external disturbances. Within these studies, postural adaptations to unanticipated force plate translations (Fujino et al., 2010; Kaji et al., 2012) and unilateral electrical stimulation of lower limbs were assessed (Hosoda et al., 2007). Overall, these studies found latencies to be significantly increased with lower jaw relaxed than those while chewing gum (Kaji et al., 2012) or submaximal clenching the teeth (Hosoda et al., 2007; Fujino et al., 2010). Interestingly, Hosoda et al. (2007) also found significant interactions between jaw clenching effects and the magnitude of external disturbances. The greater the disturbance was the shorter was the latency with occlusion. By contrast, latency increased with disturbances while non-clenching. Ultimately, these findings corroborate abovementioned results concerning static postural stability, suggesting that mastication and jaw clenching may contribute to maintenance of postural stability during unperturbed stance as well as to recovery of balance when transient and sudden perturbations appear.

Bearing in mind the various anatomical, biomechanical and neurological linkages of the CMS, the authors have argued that changes of the masticatory system could directly influence vestibular and neck sensory motor systems (Section 2.4). As the later indisputably have an important role in the control of postural balance, it has been suggested that CMS activities in this way could indirectly modulate postural control. This linkage seems to come more strongly into effect in unstable conditions or when transiently perturbed by external forces (Tardieu et al., 2009; Julià-Sánchez et al., 2015). In consequence, clenching the jaw could play an important role in postural stability and adaptation, and may further gain physiological benefits that finally could help to reduce the risk of falls among elderly or persons with diminished postural control. The scientific evidence to support this hypothesis is yet too sparse, however.

2.6 Jaw clenching and sports performance

Like with research on postural control, there have been attempts to investigate whether jaw clenching could have an effect on an athlete's performance. As briefly described previously, in natural sports environments clear masseter activity during diverse phases of action in track in field athletes, particularly during actions requiring the generation of high muscle torques (Nukaga et al., 2016). Given the spontaneous and non-parafunctional masticatory muscle activity, the authors hypothesized that jaw clenching could generally be incorporated in whole body movements, especially during strenuous activities, helping to improve systemic function.

In 1977, Stenger was the first to investigate how biting could affect muscular performance in athletes. Since then, similar to the stabilizing effects on postural control, several studies have described improvements in muscular strength and strength-related motor tasks evoked by voluntary clenching of the jaw (for review, see Forgione et al., 1991; Ebben, 2006). When the jaw was clenched, Hiroshi (2003) and Ebben et al. (2008) observed significant increases in peak force production and rate of force development during grip strength assessments and countermovement jumps. Recent research supports this ergogenic effect in terms of increased prime mover muscle activity and therefore emphasizes that jaw clenching could be a viable technique to elicit performance enhancements during dynamic and strength-related activities (Allen et al., 2016).

The phenomenon of enhanced motor output being the result of remote muscle contractions is commonly referred to as *concurrent activation potentiation*. It is supposed to rest on the stimulatory effect of remote muscle contractions that facilitates the activation of the prime movers of the targeted movements (for review, see Ebben, 2006). Given the above-depicted neurophysiologic findings, the potentiation is thought to occur mainly on cortical sites. This suggestion relates to the integrative function of the cerebral motor cortex and presumably is fostered either by a spread of activation within the cortex from face to limb motor representation (Boroojerdi et al., 2000) or by an unmasking of excitatory projections (Sugawara & Kasai, 2002). Ultimately, this facilitation may increase the corticospinal excitability and, in turn, the neural drive to the targeted muscle groups. By amplifying the muscle activity and motor output of the prime movers and its synergists

(Aboodarda et al., 2015; Allen et al., 2016), the activation of facial and masticatory muscles may also affect the control and performance of human movements (Buisseret-Delmas et al., 1999; Pinganaud et al., 1999).

Concomitant with the jaw clenching effects, the potential benefits of oral splints on athletic performance have gathered increasing attention. Ergogenic effects from use of jaw-aligning appliances have been found in measurements of muscle strength and power, possibly as a result of optimum systemic function and reduced stress on the CMS (Kaufman & Kaufman, 1985; Forgione et al., 1991; Forgione et al., 1992; Gelb et al., 1996; Arent et al., 2010; Dunn-Lewis et al., 2012). Likewise, Kwon et al. (2010) and Pae et al. (2013) observed significant improvements in driving distance and club head speed in golf professionals when the oral appliances were being used. By contrast, other studies failed to observe alteration of muscle strength as a result of the use of oral appliances (Cetin et al., 2009; Allen et al., 2014; Golem & Arent, 2015). These results are further reinforced by studies using double-blind tests, which claim that performance enhancements caused by repositioning or stabilizing splints are simply the result of placebo effects (Burkett & Bernstein, 1983; Allen et al., 1984; McArdle et al., 1984; Chiodo & Rosenstein, 1986). Hence, there is still a prevailing uncertainty regarding a potential interference of motor performance via alteration of dental occlusion.

3 Aims and Scope of this Thesis

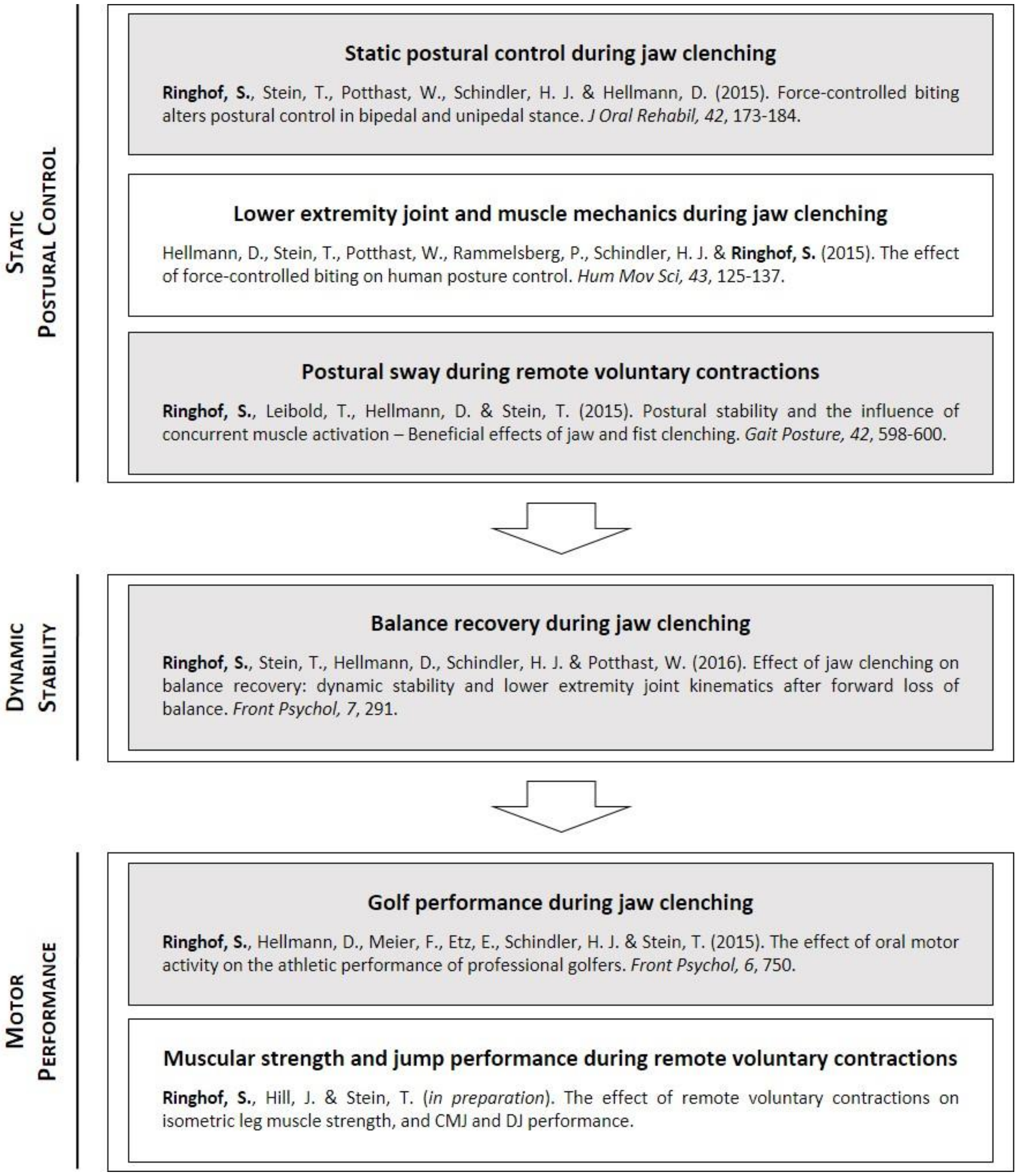
In view of the literature prepared (Sections 2.5 and 2.6), it is difficult to draw meaningful conclusions about the impact of jaw clenching on human postural control and performance. Further investigations are warranted to better clarify the existence of this correlation and to estimate whether this relation could be of clinical or (sport) scientific interest. Research in this context particularly requires a twofold need to improve the methodological quality of investigations as well as to address more specific research questions. The use of comprehensive biomechanical analyses and multiple static and dynamic balance tests to better understand the functional coupling of the CMS with human balance may prove to be of high value. This applies even more as the mechanisms of this potential interaction remain to be clarified. Furthermore, the effect of concurrent jaw clenching on postural stability under dynamic conditions has not yet been sufficiently examined.

This thesis aims to overcome the deduced research gaps and investigates the influence of submaximal jaw clenching on human postural control with special consideration of comprehensive analyses of static and dynamic stability. For this purpose, biomechanical measurements including kinematic, dynamic and electromyographic analyses are applied in conjunction with above-introduced experimental approaches. Given the improvements in muscular strength when clenching the jaw and the widespread use of oral appliances in golfers, this thesis further investigates the influence of jaw clenching on athletic performance in competitive golfers. By this means, potential ergogenic effects of jaw clenching and the use of oral appliances on human motor performance are elucidated. Accordingly, the present thesis encompasses three main research issues:

(i) influence of jaw clenching on static stability,

(ii) influence of jaw clenching on dynamic stability,

(iii) influence of jaw clenching on golf performance.



Static postural control during jaw clenching

Ringhof, S., Stein, T., Potthast, W., Schindler, H. J. & Hellmann, D. (2015). Force-controlled biting alters postural control in bipedal and unipedal stance. *J Oral Rehabil, 42*, 173-184.

Lower extremity joint and muscle mechanics during jaw clenching

Hellmann, D., Stein, T., Potthast, W., Rammelsberg, P., Schindler, H. J. & **Ringhof, S.** (2015). The effect of force-controlled biting on human posture control. *Hum Mov Sci, 43*, 125-137.

Postural sway during remote voluntary contractions

Ringhof, S., Leibold, T., Hellmann, D. & Stein, T. (2015). Postural stability and the influence of concurrent muscle activation – Beneficial effects of jaw and fist clenching. *Gait Posture, 42*, 598-600.

Balance recovery during jaw clenching

Ringhof, S., Stein, T., Hellmann, D., Schindler, H. J. & Potthast, W. (2016). Effect of jaw clenching on balance recovery: dynamic stability and lower extremity joint kinematics after forward loss of balance. *Front Psychol, 7*, 291.

Golf performance during jaw clenching

Ringhof, S., Hellmann, D., Meier, F., Etz, E., Schindler, H. J. & Stein, T. (2015). The effect of oral motor activity on the athletic performance of professional golfers. *Front Psychol, 6*, 750.

Muscular strength and jump performance during remote voluntary contractions

Ringhof, S., Hill, J. & Stein, T. (*in preparation*). The effect of remote voluntary contractions on isometric leg muscle strength, and CMJ and DJ performance.

Figure 3.1 Schema of the scientific work performed by the BioMotion Center at Karlsruhe Institute of Technology (KIT) and the Department of Prosthodontics of the University of Heidelberg. Shaded boxes indicate the work presented in this thesis.

The subsequent Chapters 4 to 7 comprise four research articles that each consider one of those main parts. Chapters 4 and 5 encompass studies examining static stability, whereas Chapters 6 and 7 focus on the assessment of dynamic stability and golf performance, respectively.

All studies were conducted at the BioMotion Center of the Institute of Sports and Sports Science at Karlsruhe Institute of Technology (KIT) and have been published in international peer-reviewed journals in the years 2015 and 2016. The studies were part of a cooperative project with the Dental School of the Department of Prosthodontics at the University of Heidelberg, which was supported by Deutsche Forschungsgemeinschaft grant HE 6961/1-1. Figure 3.1 provides a schema of the thesis-related scientific work and illustrates the integration of the four research articles to the overall projects done within this framework.

3.1 Influence of jaw clenching on static stability

As outlined in Sections 2.4 and 2.5, research suggests that some occlusal features related with malocclusions or distinct masticatory muscle activities are likely to require postural adaptation at near as well as remote musculoskeletal districts. Nevertheless, the available literature manifests a plethora of unresolved research questions. Whereas the relation between dental occlusion and postural control has extensively been investigated, however, with urgent need to improve the methodological quality of the investigations, the influence of voluntary masticatory muscle contractions on postural control has been subject to little research yet.

The study by Hellmann et al. (2011c) nicely demonstrated that the execution of controlled oral motor tasks in terms of concurrent submaximal biting has the potential to positively affect postural stability. Although these results are promising, the significance of these results suffers from some methodological deficiencies. Apart from differing occlusal conditions (maximal biting on cotton rolls as compared to submaximal biting on liquid-filled pads), particular attention should be paid to the short-term exposure of three seconds, which by far does not fulfil the recommendations for posturographic assessments. Indeed, durations greater ten seconds are vital to enable differences between postural control to be distinguished (Parreira et al., 2013). Beyond that, no studies have investigated how clenching the jaw could influence joint coordination and muscular (co-)contraction patterns within the common postural control mechanisms. Above-introduced studies in the context of jaw clenching (Section 2.5) were all restricted to the posturographic level. The underlying neuromuscular control mechanisms to explain this potential influence, hence, have not been sufficiently investigated yet. Considering these limitations combined with the limited number of posturographic parameters and experimental conditions examined, the detailed impact of jaw clenching on postural control remains elusive.

Therefore, the first objective of this cooperative work was to gain a better insight into the relationship of submaximal jaw clenching with postural balance. The initial step was to improve the methodological quality of preliminary studies as well as to extent the analyses by supplementing biomechanical methods such as three-dimensional kinematic and electromyographic analyses. By use of these methods, the first study aimed (i) to reinforce the association of jaw clenching with balance at posturographic level, (ii) to investigate potential changes in whole-body coordination and postural strategies, and (iii) to examine potential adaptations at muscular level. For this purpose, a comprehensive experiment investigating the influence of concurrent submaximal biting on static postural control with special consideration of the underlying control mechanisms was performed. This encompassed the analysis of postural stability by means of posturographic measurements as well as of upper body control in terms of trunk and head kinematics (Ringhof et al., 2015c). In addition, postural control strategies and muscular control pattern were assessed by examining lower extremity joint kinematics and electromyographic activity of six lower limb muscle groups (Hellmann et al., 2015). Chapter 4 provides a fusion of both works and highlights the neuromuscular control of static balance while concurrently submaximal clenching the jaw compared to a non-clenching control condition.

Based on this first experiment, a follow-up study was conducted. The purpose of this second experiment was to build on the findings of the initial study by concentrating on the general modulation of postural stability by concurrent submaximal clenching activities. This was considered essential as the significance of the previously gained findings was limited by the lack of active controls, such as used by Miyahara et al. (1996). The authors reported that soleus H-reflex is not only increased by voluntary clenching of the teeth but also by isometric contraction of the wrist extensors or by clenching of the fists. This finding rose the question as to whether postural adaptations could also be observed among other remote voluntary contractions. Furthermore, comparisons with habitual control conditions and investigations on postural stability under more complex postural conditions have not previously been addressed. Consequently, the aims of the second experiment were threefold: (i) to ascertain the general influence of concurrent muscle activation on postural stability, (ii) to compare the effects of submaximal clenching activities to a habitual control condition, and (iii) to reproduce the gained finding on foam surfaces, i.e., when the proprioceptive system is challenged. This follow-up study is presented Chapter 5 (Ringhof et al., 2015b).

3.2 Influence of jaw clenching on dynamic stability

The second main research question of this thesis considers balance control under dynamic conditions. In contrast to static stability, which concerns balance control during upright unperturbed standing, dynamic postural stability refers to balance control either in advance or in response to internal and external disturbances (Horak, 2009). Hence, dynamic stability is an important prerequisite for maintaining stability while, e.g., walking or reaching to grasp a glass, and also plays a certain role in athletic performance (Wakano et al., 2011).

Due to its less simple application and evaluation, researchers frequently avoid investigations of dynamic postural stability. The practical value of dynamic stability assessment is considerably high, however. In daily life, the majority of falls are due to external disturbances and most frequently occur during locomotion, such as stumbling and slipping while walking (Blake et al., 1988; Niino et al., 2000). Scientifically, moreover, the individual risk of falling is well-known to be much more related to dynamic as compared to static postural control (Rubenstein, 2006). Knowledge about balance control under dynamic conditions therefore provides valuable information for fall prevention and rehabilitation.

Despite its great significance for various fields, the issue of how dynamic balance could be influenced by changes of the CMS or oral motor activity per se has not previously been adequately investigated. Nevertheless, above-introduced studies (Section 2.5) suggest that chewing or voluntary jaw clenching could contribute to maintenance or recovery of postural balance (Hosoda et al., 2007; Fujino et al., 2010; Kaji et al., 2012). For instance, this facilitation might help to prevent people from falling when rapid or unexpected perturbations occur. The physiological significance of this maneuver in an everyday fall situation yet remains to be clarified.

The study depicted in Chapter 6 addresses this latter issue and extends on the experiments on static postural control (Ringhof et al., 2016). Specifically, this study investigated whether clenching the jaw could improve reactive balance recovery and by this means could have the potential to reduce the risk of falls. For this purpose, above-introduced approach of simulated forward falls was applied. Using biomechanical motion analyses, this study further examined potential changes in spatiotemporal parameters and lower extremity joint kinematics under these conditions.

3.3 Influence of jaw clenching on golf performance

Section 2.6 has briefly introduced the potential impact that jaw clenching activities may have on sports performance. In particular, several reports described performance enhancements, especially improvements in muscular strength and strength-related motor tasks (for review, see Forgione et al., 1991; Ebben, 2006). The spontaneous masticatory muscle activity observed during strenuous activities furthermore suggests that clenching the jaw might be a physiological strategy that may be employed to augment the activation of targeted muscle groups (Ebben, 2006). From a sports scientific and dentistry viewpoint, it is highly interesting (i) to clarify the physiological significance of mastication muscles' activity, and (ii) to gather knowledge about the potential benefits athletes may gain from voluntary remote muscle contractions.

The final main part of the cooperative work considers this issue and focuses on human motor performance under the impact of concurrent oral motor activity. Two experiments were carried out in this context, one of which is depicted in Chapter 7 (Ringhof et al., 2015a). Therein, the performance of competitive golfers was examined by application of golf shot analyses. In particular, it was assessed if submaximally clenching the jaw could impart positive effects on shot length and shot precision over three different shot distances.

As briefly depicted previously, ergogenic effects on sports performance have also been described for the use of jaw-aligning appliances, inter alia in golf professionals (Kwon et al., 2010; Pae et al., 2013). Due to weak experimental designs and lack of control conditions, some of this work has been criticized, however (Jakush, 1982; McArdle et al., 1984). This discrepancy is further supported by studies that either have failed to observe any alterations or have found performance enhancements to be the result of placebo effects (Burkett & Bernstein, 1983; Allen et al., 1984; McArdle et al., 1984; Chiodo & Rosenstein, 1986). The study in Chapter 7 expands on this controversy and further investigates whether ergogenic effects of oral appliances could also apply for achieving maximum performance in golf sports. For this purpose, golf shots were analyzed while athletes were submaximally biting on an intra-oral splint. In that way, this study examined if clenching effects are superior for biting on an oral splint than for biting on one’s teeth.

4 Modulation of Static Postural Control during Concurrent Jaw Clenching

Extended version of the publication

Ringhof, S., Stein, T., Potthast, W., Schindler, H. J. & Hellmann, D. (2015). Force-controlled biting alters postural control in bipedal and unipedal stance. *Journal of Oral Rehabilitation*, *42*, 173-184. doi: 10.1111/joor.12247

4.1 Abstract

Human posture is characterized by inherent body sway, which forces the sensory and motor systems to counter the destabilizing oscillations. Although the potential of biting to increase postural stability has recently been reported, the mechanisms by which the craniomandibular system (CMS) and the motor systems for human postural control are functionally coupled are not yet fully understood. The purpose of the present study was, therefore, to investigate the effect of submaximal biting on postural sway and the kinematics of the trunk and head, as well as on joint kinematics and muscular activities of the lower extremities. Twelve healthy young adults participated in this study and performed force-controlled biting (FB) and non-biting (NB) during bipedal narrow stance and single-leg stance. Bite forces were measured using a hydrostatic splint while postural sway was quantified based on center of pressure (CoP) displacements, detected by use of a force platform. Trunk and head kinematics as well as lower extremity joint kinematics were investigated by biomechanical motion analyses. Electromyographic activity of the leg muscles was recorded to analyze the mean activities and the variability of muscular co-contraction ratios (VCoR) of six postural muscles. The results revealed that FB significantly improved postural control in terms of reduced COP displacements, providing additional evidence for the functional coupling of the CMS and human posture. Our study also showed, for the first time, that reductions in the sway of the COP were accompanied by reduced trunk and head oscillations, decreased joint motions in both frontal and sagittal planes, and reduced VCoR for three of the four muscle pairs studied. As the reductions of joint motions were systematically across all joints considered and trunk kinematics revealed no changes in balance control strategies, it is concluded that the improvements in postural control during FB are not attributable to any changes of the basic control strategies, but rather to an increased kinematic precision among the neuromuscular control patterns. Partial correlations, which indicated no significant associations between CoP measures and VCoR, support this assumption. The physiological response to isometric activation of the masticatory muscles observed in this study raises questions about the potential of oral motor activity as a strategy to reduce the risk of falls among elderly or patients with compromised postural control.

4.2 Introduction

Human posture is characterized by inherent instability, known as ‘body sway’. Corrective intermuscular and intramuscular synergy and coordination of the different body regions are needed to counteract the destabilizing oscillations arising from internal and external forces (Loram & Lakie, 2002). The control of the body’s position in space for the purposes of stability and orientation is referred to as ‘postural control’ (Shumway-Cook & Woollacott, 2011). Sensory information from the visual, vestibular and somatosensory systems is important input for controlling posture. This information is passed to the different parts of the central nervous system (CNS), where it is integrated and dynamically re-weighted to provide an internal representation of the body and its environment (Macpherson & Horak, 2013). This representation is then used by the higher centers of the CNS to generate and update the motor commands that maintain postural equilibrium. The process of balancing is thus predominantly based on feedback mechanisms involving complex interaction of the sensory and motor systems (Peterka & Loughlin, 2004).

Studies on animals have provided information about the neuroanatomical connections of the nervus trigeminus to vestibular and oculomotor nuclei (Buisseret-Delmas & Buisseret, 1990; Buisseret-Delmas et al., 1999). Projections from trigeminal nuclei to all levels of the spinal cord and to the vestibulo-cerebellum have also been found (Ruggiero et al., 1981; Alstermark et al., 1992; Pinganaud et al., 1999; Devoize et al., 2010). Taking this neuromuscular integration of the craniomandibular system (CMS) into account, it has been shown that motor activity during jaw clenching contributes to the facilitation of postural reflexes (Miyahara et al., 1996; Boroojerdi et al., 2000; Takada et al., 2000) in a manner similar to the Jendrassik maneuver (Jendrassik, 1885; Dowman & Wolpaw, 1988; Bischoff, 2002). Furthermore, posturographic analysis during quiet stance revealed physiological effects of biting under different occlusal conditions on the stabilization of human posture (Gangloff et al., 2000; Bracco et al., 2004; Sforza et al., 2006; Tardieu et al., 2009). In contrast to maximum biting, body sway was significantly reduced during submaximal biting, and the center of pressure (CoP) deviated significantly in the anterior direction (Hellmann et al., 2011c). The authors explained these results on the basis of stiffening of the anterior myofascial chains, which seems to be one component of common motor reactions to new or unfamiliar motor tasks and might, thus, be a strategy for facilitating reflexes and preventing falls (Carson & Riek, 2001; Hellmann et al., 2011c).

Although posturographic measurement of the CoP provides relevant information about the general effects of biting on postural stability, no information is yet available about the coordination of upper and lower body segments under these conditions. Moreover, to the best of the authors' knowledge, none of the mentioned posturographic studies investigated the underlying neuromuscular mechanism of the measured phenomena, and also the effect of biting on postural control during more complex balance tasks has not been studied. Such work could provide evidence of the potential of oral motor activity as a strategy for patients with compromised postural control to reduce the risk of falls.

The purpose of this study was, therefore, to comprehensively investigate the effects of submaximal CMS motor activity on postural control in bipedal narrow stance and single-leg stance by means of posturographic, kinematic and electromyographic analyses. It was hypothesized that force-controlled biting improves postural control in terms of decreased CoP displacement concomitant with decreased oscillations of the trunk and head. Further, it was suggested that stiffness during biting is significantly increased and that participants, hence, rely more on ankle than on hip strategy to control balance. This in turn was thought to be interrelated with modulations in joint kinematics and patterns of muscular co-contractions.

4.3 Material and methods

4.3.1 Subjects

Twelve young adults (age 21.8 ± 1.8 years; 10 male, 2 female) participated in our exploratory study. The subjects' body mass index was 22.9 ± 3.7 kg/m^2, and reported weekly physical activity was 2.3 ± 1.2 h. The participants had no known muscular or neurological diseases that could have affected their ability to perform the experiments. Moreover, they all had normal vision and no temporomandibular disorders, as assessed by means of the RDC/TMD criteria (Dworkin & LeResche, 1992), and presented with full dentition (except for third molars) in neutral occlusion. All participants gave their written informed consent to the experiments, which were conducted in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of the German Sport University Cologne (no. 38/12).

4.3.2 Apparatuses

Bite force was measured by use of a hydrostatic system consisting of liquid-filled pads fixed to the maxilla by means of an occlusal splint with a planar surface (Figure 4.1). A corresponding planar splint stabilized the mandible in an instructed centric relation position (Hellmann et al., 2011c). Biting on the pads resulted in increased hydrostatic pressure, which was sampled at 1000 Hz and presented to the participants as numerical real-time feedback on a screen positioned at eye level 4.0 m in front of the subjects.

To investigate the effect of submaximal biting on static balance, coordination of upper body segments, joint kinematics, and muscular activity of the lower extremities, valid and reliable tools for posturographic, kinematic and EMG analyses were used (Robertson et al., 2004; Hellmann et al., 2011a). Postural stability and postural sway were quantified from CoP time series collected by use of a force platform (AMTI, model BP600900; Advanced Mechanical Technology, Watertown, MA, USA). The force platform was positioned in the floor and sampled at 1,000 Hz.

Kinematic data were recorded with a commercially available opto-electronic system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK), operating at 200 Hz. Motion capture systems as Vicon are considered as the gold standard for 3D motion

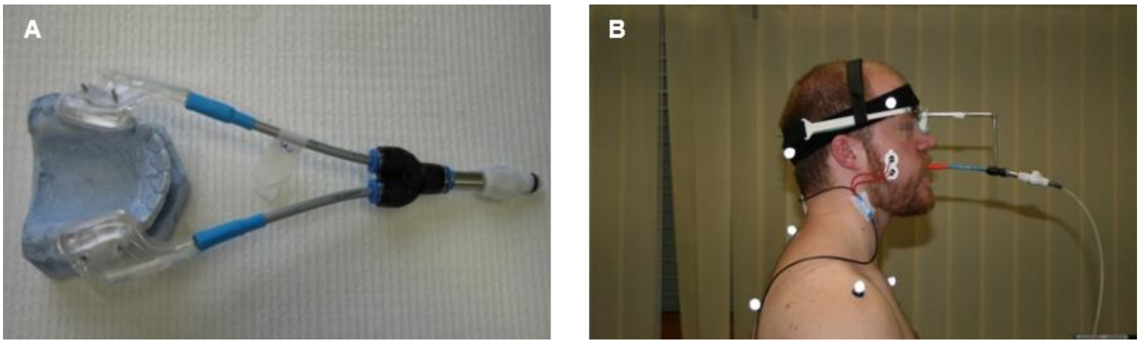


Figure 4.1 Hydrostatic bite force measurement system. **A**, intra-oral device with liquid-filled pads; **B**, attachment to the head.

analyses (Richards, 1999; Robertson et al., 2004; Barker et al., 2006; Winter, 2009; Carse et al., 2013). They principally use infrared cameras that track passive reflective markers attached to the subject's skin (Figure 4.2). Based on these data, human multibody models (Davis, Õunpuu, Tyburski & Gage, 1991; Kadaba, Ramakrishnan & Wootten, 1990) allow for the definition of rigid body segments and its CoMs, as well as of joint centers and its motions. The 3D position of each marker over time is calculated with an accuracy better than 1.0 mm. In the present study, markers coordinates were collected by 13 infrared cameras (Vicon MX camera system; resolution 1280 × 1024 pixels). Thirty-nine reflective markers (diameter 14 mm) were placed on anatomical landmarks of the participants in accordance with the Vicon Plug-in Gait full-body marker set (Vicon Motion Systems, 2010). Detailed information on the marker set can be found in Appendix S1.

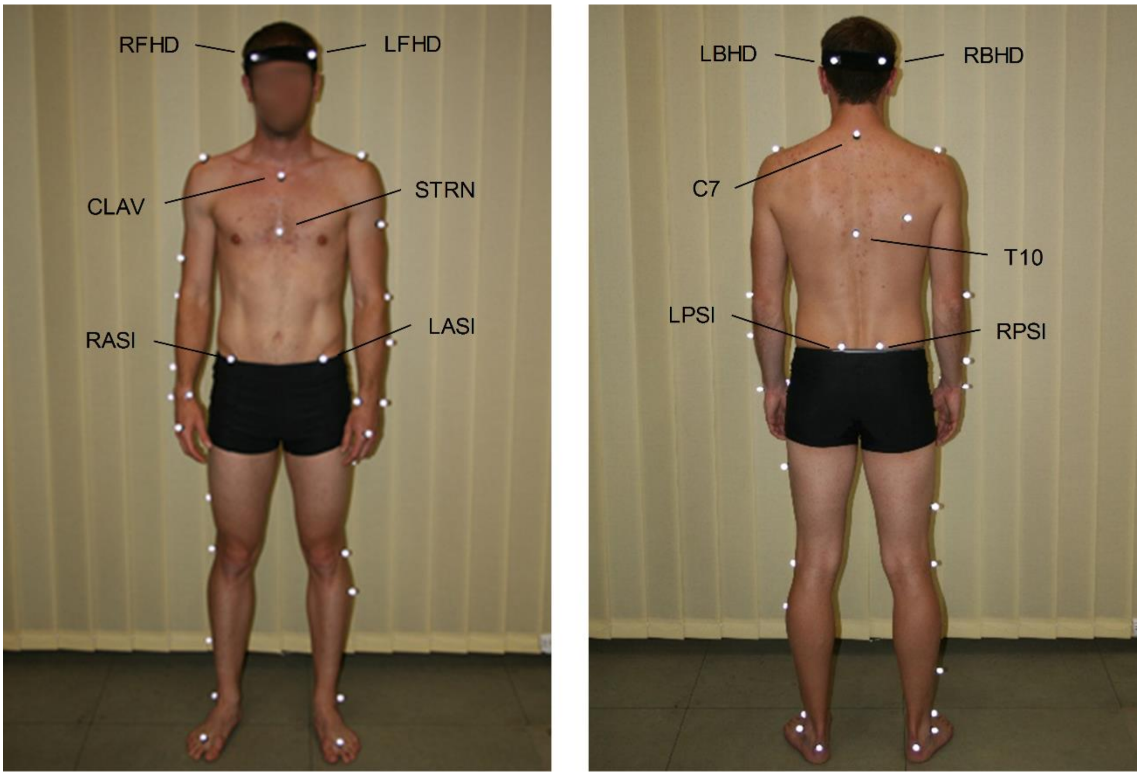


Figure 4.2 Positioning of reflective markers on the subject's skin in accordance with the Vicon Plug-in Gait full-body marker set (Vicon Motion Systems, 2010).
RFHD = right front head; LFHD = left front head; LBHD = left back head; RBHD = right back head; CLAV = clavicle; STRN = sternum; C7 = 7th cervical vertebrae; T10 = 10th thoracic vertebrae; RASI = right anterior superior iliac spine; LASI = left anterior superior iliac spine; LPSI = left posterior superior iliac spine; RPSI = right posterior superior iliac spine.

Electromyographic activity of the masseter (MA), as well as of tibialis anterior (TA), soleus (SO), gastrocnemius medialis (GM), rectus femoris (RF), vastus medialis (VM), and biceps femoris (BF) was recorded by use of bipolar surface electrodes (Ag/AgCl) and Noraxon telemetric equipment (TeleMyo 2400 G2; Noraxon, Scottsdale, AZ, USA). Before application, the skin over the participants' muscles was properly prepared by shaving, abrasion, and cleaning with alcohol. The electrodes, which had a diameter of 14 mm and a center-to-center distance of 20 mm, were then applied bilaterally to the belly of the muscles, in line with the direction of the muscle fibers. After placement of the electrodes, the raw EMG data were checked for artefacts, and maximum voluntary contractions (MVC) for each muscle were performed (Hellmann et al., 2015). The EMG signals were collected with a sampling frequency of 1,500 Hz, simultaneously with the pressure, posturographic and kinematic data.

4.3.3 Experimental procedure

All subjects warmed up on a treadmill for 5 min at 1.8 m/s. Before the experiments, subjects were given standardized verbal instructions about the oral motor tasks and the bipedal and unipedal stances.

Oral motor tasks

The subjects performed two types of oral motor task–force-controlled biting (FB) and non-biting (NB), which served as the control condition. Force-controlled biting was performed at submaximal bite forces of 150 N, in accordance with previous experiments (Hellmann et al., 2011c), and corresponded to mean individual MVC of the masseter of 15.07 ± 4.47%. Before biting on the pressure pads, the subjects were instructed to position the mandible in centric relation, initially guided by an experienced dentist. This position was stabilized by horizontal force components of the bite force, because the pads were fixed to the maxilla and the plane surfaces of the splints acted as a wedge under the applied bite forces, automatically constraining the mandible posteriorly. In addition to this mechanical consideration, a stable jaw position was confirmed, as in a previous study (Hellmann et al., 2011c), by use of an ultrasonic 3D jaw motion analysis system that recorded jaw position stability for several subjects during the biting experiments.

The oral device was also worn in NB. The subjects were, however, asked to keep their mandible in a resting position, that is consciously applying no bite force, and monitoring this condition by looking at the feedback screen. This control condition was chosen to avoid divergent cognitive demands between the two oral motor tasks, because it is known that secondary cognitive tasks can affect postural stability differently (Woollacott & Shumway-Cook, 2002). Thus, if cognitive tasks do affect postural stability, and if oral motor tasks require cognitive attention, their effect in our study should be negligible.

Bipedal and unipedal stances

All participants performed both oral motor tasks during bipedal narrow stance and during unipedal stance on their dominant and non-dominant legs. These support conditions are frequently used as methods to determine postural differences in diverse research investigations (Henriksson et al., 2001; Gribble & Hertel, 2004b; Bisson et al., 2011; Huurnink et al., 2014; Lee & Powers, 2014).

In bipedal narrow stance, the subjects stood barefoot, on both feet, on the force platform, with the medial sides of the feet touching each other. In unipedal stance, the subjects were instructed to maintain posture without support from the elevated leg while standing barefoot on the force platform. The leg the subjects used to jump with and land on in single-leg jumps was regarded as dominant. Irrespective of the support condition (bipedal, dominant, non-dominant), the subjects were instructed to maintain an upright position, with their arms hanging at their sides, and to stand as still as possible. They were asked to breathe normally, and to look straight ahead, focusing on the feedback screen. The anteroposterior (AP) position and mediolateral (ML) alignment of the supporting limb(s) were determined by use of marks on the platform. The elevation of the non-supporting leg in unipedal stance was intra-individually standardized with a laser pointer.

Experimental design

The order of the support conditions was assigned randomly to the subjects. Counterbalanced, half of the sample started balancing while applying the submaximal bite force, whereas the other group first performed balancing with the mandible at rest. Before changes of the support and biting conditions, the subjects were familiarized with the tasks.

All the subjects then completed five valid trials for each of the six test conditions. A trial was considered valid when the intended bite force was maintained within ± 20% throughout the trial. Considering the effort of submaximal biting, recording time was predetermined as 10 s separated by 30-s intervals. Measurements were started when the intended bite force was reached.

4.3.4 Data analysis

For each testing condition, all five trials were included in the evaluation. Posturographic and kinematic data were processed by use of Vicon Nexus software, whereat the three-dimensional coordinates of the reflective markers initially were reconstructed and labeled in accordance with the Vicon Plug-in Gait full-body marker set (Vicon Motion Systems, 2010). Thereafter, time series of the CoP and the kinematic data were digitally filtered by use of a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz.

Processing of EMG data was performed by use of MyoResearch XP Master Edition (Noraxon, Scottsdate, USA). Within this framework, root mean square (RMS) values were calculated and then scaled to the MVC data (Hellmann et al., 2015). As balance in bipedal narrow and unipedal stance is controlled by use of rapid adjustments in the form of intermittent stabilization bursts (Loram & Lakie, 2002; Morasso & Sanguineti, 2002), the RMS values in this study were obtained using a short smoothing window of 30 ms (Sinkjær & Arendt-Nielsen, 1991; Hortobágyi et al., 2005; Hatton et al., 2011; Barbado et al., 2012; Hellmann et al., 2015). Based on the preprocessed data, different posturographic, kinematic and EMG variables were calculated.

CoP measures

The average AP and ML positions of the CoP were determined relative to the center of the base of support (BoS), calculated on the basis of the reflective markers placed on the subjects' feet. Postural stability was quantified by the minimum spatial margin of stability (MoS_{min}), which is defined as the minimum distance of the CoP to the anterior boundary of the BoS, represented by the reflective markers placed on the subjects' toes (Hof et al., 2005). The MoS_{min} concept suggests that postural stability in AP direction decreases as the MoS_{min} approaches zero.

Postural sway was calculated on the basis of the CoP displacements, as represented by the area of the 95% confidence ellipse (subsequently referred to as 'sway area') and the CoP path length, the latter in the AP and ML directions. The sway area is an indicator of the spatial variability of the CoP (Vuillerme et al., 2008), whereas the path lengths describe the direction and extent of postural sway (Clark & Riley, 2007). Use of these variables enables assessment of postural stability during unperturbed stance with high to excellent reliability (Bauer et al., 2010; Pinsault & Vuillerme, 2009; Ruhe et al., 2010). In this study, intra-session reliability of CoP sway measures, estimated by use of intra-class correlation coefficients ($ICC_{3,1}$), ranged from 0.607 to 0.961 (Table 4.1), revealing reliability was good to excellent (Fleiss, 1986). The mean intra-individual variability – measured as the coefficient of variation – was 38.50% for sway area, 14.82% for AP path length and 15.83% for ML path length.

Trunk and head kinematics

On the basis of the preprocessed data, diverse kinematic variables were computed for the upper body and the lower extremities. With respect to the upper body, kinematics were calculated for the pelvis (PELVIS), torso (TORSO) and head (HEAD) in the transverse plane. To this end, first the centers of PELVIS, TORSO, and HEAD were determined by the respective body segments – left and right anterior and posterior superior iliac spine for PELVIS; clavicle, sternum, 7th cervicle vertebrae and 10th thoracic vetebrae for TORSO; left and right front and back head for HEAD (Figure 4.2). Thereafter, the sway area, sway path lengths in AP and ML directions, and the mean positions relative to the BoS were calculated for each of the body segments. Intra-session reliability of sway measures for PELVIS, TORSO, and HEAD ranged from good to excellent (Table 4.1), and mean intra-individual variability was 49.04 to 49.45%, 3.80 to 4.93%, and 8.32 to 9.11% for sway area, AP and ML path lengths, respectively.

To additionally provide information about the control strategy used under the different test conditions, coordination of the upper body segments was computed by contrasting the movement patterns of PEVLIS and TORSO. Hereto, first the segments' velocities were calculated in frontal and sagittal planes, which were then used to extrapolate the percentage of time frames the PELVIS and TORSO moved into the same or opposite

Table 4.1 Intra-session reliability of postural sway measures.

Variable	CoP	PELVIS	TORSO	HEAD
Sway area [mm²]	0.607–0.945	0.723–0.865	0.747–0.875	0.753–0.876
AP path length [mm]	0.905–0.961	0.800–0.936	0.842–0.929	0.890–0.944
ML path length [mm]	0.749–0.946	0.880–0.992	0.884–0.988	0.884–0.986

AP = anteroposterior; ML = mediolateral.
Ranges of intra-session reliability across the different testing conditions as revealed by intra-class correlation coefficients ($ICC_{3,1}$): Poor reliability: < 0.4; fair reliability: 0.40–0.59; good reliability: 0.60–0.74; excellent reliability: > 0.75 (Fleiss, 1986).

directions, respectively. This measure suggests whether balance is primarily controlled by the ankle or hip strategy. For instance, if the percentage of frames with reversed movement direction of PELVIS and TORSO (RevMotion) is low, an enhanced ‘ankle strategy’ must be assumed, indicating that sway regulation closely resembles balancing a single-segment inverted-pendulum pivoting about the subtalar joint (Winter, 1995). If RevMotion is high, however, posture is primarily controlled by the ‘hip strategy’. Herein, two inverted-pendulum systems are present; first, the total body pivots about the supporting subtalar joint, and second, the upper body pivots about the hip joint (MacKinnon & Winter, 1993; Winter, 1995). Hence, the larger the RevMotion value, the more the participants rely on the hip strategy.

Joint kinematics

The biomechanical models described above, furthermore, allowed for the definition of joint coordinate systems and, therefore, calculation of joint kinematics at the lower extremities. Those data were used to assess the amount of compensatory movements induced by rotations about the ankle, knee and hip joint. To this end, the mean angular velocities of abovementioned joints were analyzed in frontal (AngVel front) and sagittal planes (AngVel sag), respectively.

EMG

EMG analyses finally were used to investigate the neuromuscular responses in distal muscle groups, and by this means to detect potential interactions with biting. In a first instance, for all muscles recorded the mean values of the normalized EMG for each trial were calculated. To further assess possible changes in the simultaneous activation of antagonistic muscles, the co-contraction patterns of four muscles pairs (TA/SO, TA/GM, RF/BF, VM/BF) was obtained. Hereto, for each sample point the co-contraction index (CCI) was calculated as follows:

$$CCI_i = \frac{EMG_{low_i}}{EMG_{high_i}}$$

where EMG_{low_i} and EMG_{high_i} represent the activation of the less active and more active muscles, respectively. Based on these data, the coefficients of variations of the CCIs were assessed to compare the variability of the co-contraction ratios (VCoR) (Hellmann et al., 2015).

4.3.5 Statistics

All statistical tests were performed by use of IBM SPSS Statistics 20.0 (International Business Machines Corp., Armonk, NY, USA). First, Kolmogorov–Smirnov and Mauchly’s tests were used to confirm the normality and sphericity, respectively, of the data distribution. Greenhouse–Geisser estimates were used to correct for violations of sphericity.

One-sample *t*-tests were then conducted to analyze discrepancies between requested and generated bite forces. Differences between submaximal bite forces under the different support conditions were investigated by one-way repeated measures ANOVA, whereat follow-up Bonferroni corrections were used for multiple comparisons. The effects of oral motor tasks [FB, NB] and support conditions [bipedal, dominant, non-dominant] on CoP measures, trunk and head kinematics, joint kinematics and EMG data were analyzed by two-way repeated measures ANOVAs, adjusted by use of Bonferroni corrections for multiple comparisons. The effects of support condition on relative ML positions of CoP, PELVIS, TORSO and HEAD, however, were only compared between dominant and non-dominant legs. Statistical differences for the factors under investigation are reported by the level of significance, and partial eta-squared (η_p^2) is indicated to give information about effect sizes. For large effects $\eta_p^2 = 0.14$, for medium effects $\eta_p^2 = 0.06$, and for small effects $\eta_p^2 = 0.01$ (Cohen, 1992).

Finally, partial correlations were computed to detect potential associations of CoP measures with RevMotion, joint kinematics and EMG data, respectively. The effects of oral motor tasks and sex were removed throughout the tests, whereat separate correlations were calculated for bipedal and unipedal stances (pooled data for dominant and non-dominant stances). Besides, exclusively variables that covered the same planes of movement were included in the analyses. Associations between the variables under investigation are reported by their correlation coefficient r. Values of $r = 0.10$ indicate small, $r = 0.30$ medium, and $r = 0.50$ large correlations (Cohen, 1988).

The level of significance for all statistical tests was a priori set to $p = 0.05$. All data are reported as mean values and 95% confidence intervals (mean ± $\text{CI}_{95\%}$).

4.4 Results

The submaximal bite force of 150 N, corresponding to 0.3 bar hydrostatic pressure within the pads, was maintained by the subjects throughout measurements in bipedal (0.303 ± 0.003 bar), unipedal dominant (0.302 ± 0.006 bar) and unipedal non-dominant (0.302 ± 0.004 bar) stances. Statistical tests revealed no significant differences either of the effectively generated bite forces from the intended bite forces or among the applied bite forces under the three support conditions.

CoP measures

Regarding the relative AP and ML positions, the CoP was invariably located anterior and lateral to the center of the BoS (Table 4.2). However, the locations were not significantly altered by oral motor tasks or support conditions. There were also no interaction effects.

Figure 4.3 shows the CoP sway measures as functions of the test conditions under investigation. The respective p values and effect sizes are listed in Table 4.3. Referring to MoS_{min}, two-way repeated measures ANOVA revealed no significant difference between oral motor tasks. In contrast, main effects of oral motor tasks were indicated for CoP sway area and CoP path length in AP and ML directions. Compared with standing with the mandible at rest, submaximal biting significantly reduced CoP sway area. For CoP path length in AP and ML directions, ANOVA revealed significantly smaller postural sway during FB as well. With respect to the support conditions, main effects were found for MoS_{min}. *Post hoc* analysis indicated that postural stability during bipedal stance was significantly improved as compared to unipedal dominant [*p* = 0.018] and non-dominant stances [*p*= 0.026]. Furthermore, significant main effects of support conditions were shown for CoP sway area. Bonferroni adjustments revealed that the differences between bipedal stance and dominant leg [*p* = 0.017] and between bipedal stance and non-dominant leg [*p* = 0.036] were statistically significant, but those between dominant and non-dominant legs were not. Moreover, there were significant support effects for CoP path length in AP and ML directions. In bipedal stance, the subjects swayed significantly less

Table 4.2 Relative AP and ML positions of CoP, PELVIS, TORSO, and HEAD as functions of oral motor tasks.

	Support	AP position [mm]		ML position [mm]	
		FB	NB	FB	NB
CoP	Bp	22.97 ± 10.17	21.14 ± 9.76	2.31 ± 3.17	3.53 ± 2.65
	UpD	34.49 ± 6.80	31.04 ± 6.65	6.17 ± 1.97	6.65 ± 1.35
	UpN	29.36 ± 9.08	30.56 ± 9.82	6.45 ± 3.09	6.20 ± 3.82
PELVIS	Bp	-53.87 ± 15.36	-58.17 ± 14.04	11.72 ± 8.27	11.12 ± 7.64
	UpD	-41.71 ± 15.71	-46.18 ± 14.33	49.25 ± 23.39	50.02 ± 24.74
	UpN	-46.35 ± 20.57	-45.30 ± 21.05	55.35 ± 25.09	56.62 ± 25.05
TORSO	Bp	-6.98 ± 17.08	-12.38 ± 15.56	-10.75 ± 8.59	-10.35 ± 7.17
	UpD	9.91 ± 17.33	4.37 ± 14.72	56.34 ± 27.73	57.25 ± 28.27
	UpN	3.25 ± 21.67	3.62 ± 21.91	48.31 ± 23.66	50.43 ± 24.84
HEAD	Bp	22.71 ± 35.52	25.80 ± 17.84	5.03 ± 8.76	5.63 ± 7.37
	UpD	52.73 ± 20.10	46.62 ± 16.72	48.42 ± 25.36	49.34 ± 26.47
	UpN	46.36 ± 23.71	46.59 ± 23.99	52.95 ± 23.26	55.43 ± 23.63

Positions of the CoP, PELVIS, TORSO, and HEAD relative to the center of the base of support. Negative values indicate posterior, and right (bipedal) or medial (unipedal) locations, respectively. All data are presented as mean ± $\text{CI}_{95\%}$.
AP = anteroposterior; ML = mediolateral; FB = force-controlled biting; NB = non-biting.
Two-way repeated measures ANOVA: All comparisons were not statistically significant.

than on the dominant [AP: $p < 0.001$; ML: $p < 0.001$] and non-dominant [AP: $p < 0.001$; ML: $p < 0.001$] legs. Contrastingly, there were no significant differences between results for the dominant and non-dominant legs, and no interaction effects for any posturographic variable.

Trunk and head kinematics

As can be obtained from Table 4.2, neither AP nor ML positions of any of the body segments deviated significantly between oral motor tasks and support conditions. Apart from this, no significant interactions were observed. Figure 4.4 shows the sway variables of interest for PELVIS, TORSO, and HEAD as functions of the test conditions under investigation. The *p* values and effect sizes are reported in Table 4.3.

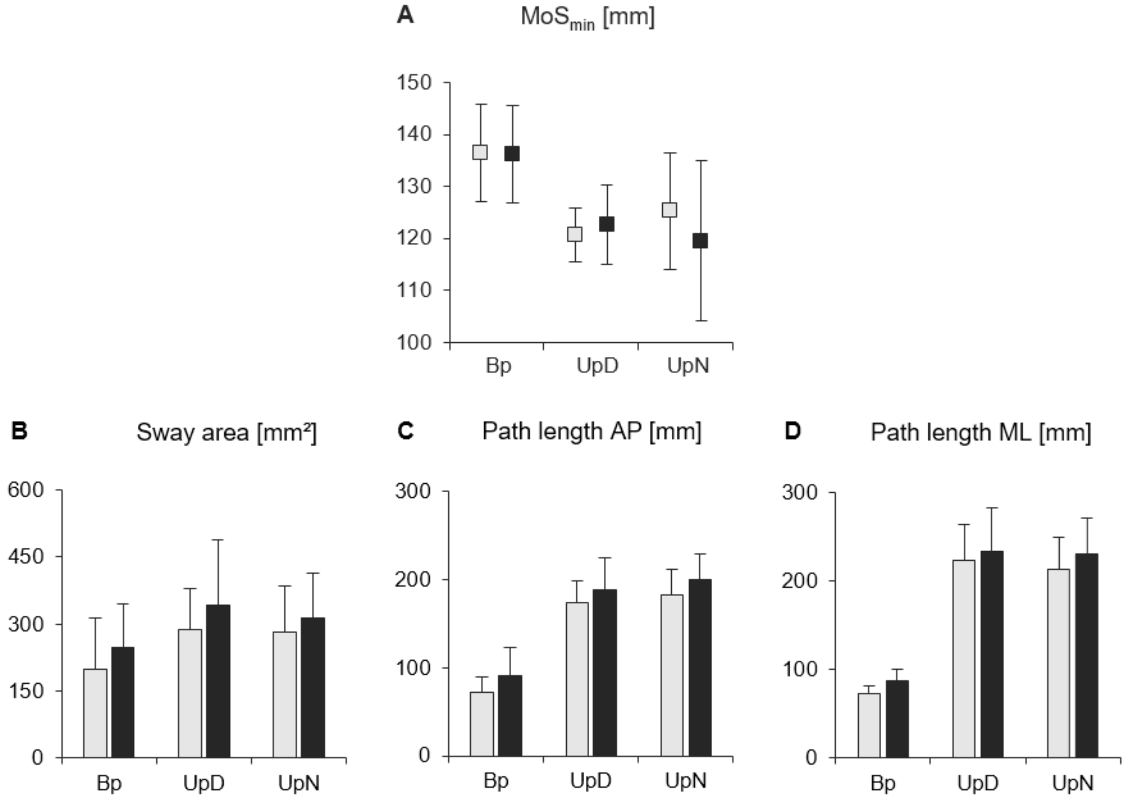


Figure 4.3 CoP measures for force-controlled biting (grey) and non-biting (black) during bipedal (Bp), unipedal dominant (UpD) and unipedal non-dominant stances (UpN). **A**, minimum margin of stability (MoS_{min}); **B**, CoP sway area; **C**, CoP path length in anteroposterior direction (AP); **D**, CoP path length in mediolateral direction (ML). All data are presented as mean ± $CI_{95\%}$.

Table 4.3 *P* values and effect sizes of postural sway measures for the different test conditions.

	Variable	Oral motor task		Support condition		Interaction	
		p	η_p^2	p	η_p^2	p	η_p^2
CoP	MoS_{min} [mm²]	0.466	0.05	0.017*	0.31	0.268	0.11
	Sway area [mm²]	0.005*	0.53	0.001*	0.45	0.771	0.02
	AP path length [mm]	0.007*	0.50	< 0.001*	0.82	0.922	0.01
	ML path length [mm]	0.030*	0.36	< 0.001*	0.86	0.741	0.03
PELVIS	Sway area [mm²]	0.210	0.14	0.034*	0.26	0.415	0.08
	AP path length [mm]	0.015*	0.43	0.390	0.08	0.173	0.15
	ML path length [mm]	0.024*	0.38	0.295	0.10	0.638	0.03
TORSO	Sway area [mm²]	0.224	0.13	0.031*	0.32	0.371	0.08
	AP path length [mm]	0.009*	0.48	0.375	0.09	0.228	0.13
	ML path length [mm]	0.020*	0.40	0.257	0.12	0.406	0.07
HEAD	Sway area [mm²]	0.256	0.12	0.032*	0.32	0.379	0.08
	AP path length [mm]	0.005*	0.53	0.634	0.04	0.179	0.15
	ML path length [mm]	0.017*	0.42	0.211	0.14	0.317	0.09

MoS_{min} = minimum margin of stability; AP = anteroposterior; ML = mediolateral.
P values and effect sizes (η_p^2) as revealed by two-way repeated measures ANOVA: * statistically significant; small effect: $\eta_p^2 = 0.01$; medium effect: $\eta_p^2 = 0.06$; large effect: $\eta_p^2 = 0.14$ (Cohen, 1992).

With respect to PELVIS, FB had no statistically significant effect on sway area. In contrast, submaximal biting resulted in significant reductions of sway path length in AP and ML directions. Changing the support condition merely induced significant alteration of the sway area. The submaximal biting task also resulted in significant sway alterations for TORSO. Compared with NB, the AP and ML path lengths were significantly shortened during FB. However, FB did not influence the sway area. Apart from that, sway area was significantly affected by the support conditions. For HEAD, the AP and ML path lengths, again, were both indicative of improved stability during FB. With regard to the three support conditions, ANOVA only revealed statistically significant differences for sway area. For all body segments and variables under investigation, no interaction effects were apparent.

Considering RevMotion, descriptively, percentages of times frames with reversed movement directions were entirely low, ranging from 12.10 to 25.69%. Hence, PELVIS and TORSO mainly moved in equivalent directions (Figure 4.5). Statistically, repeated measures ANOVAs indicated that oral motor tasks did not significantly affect RevMotion

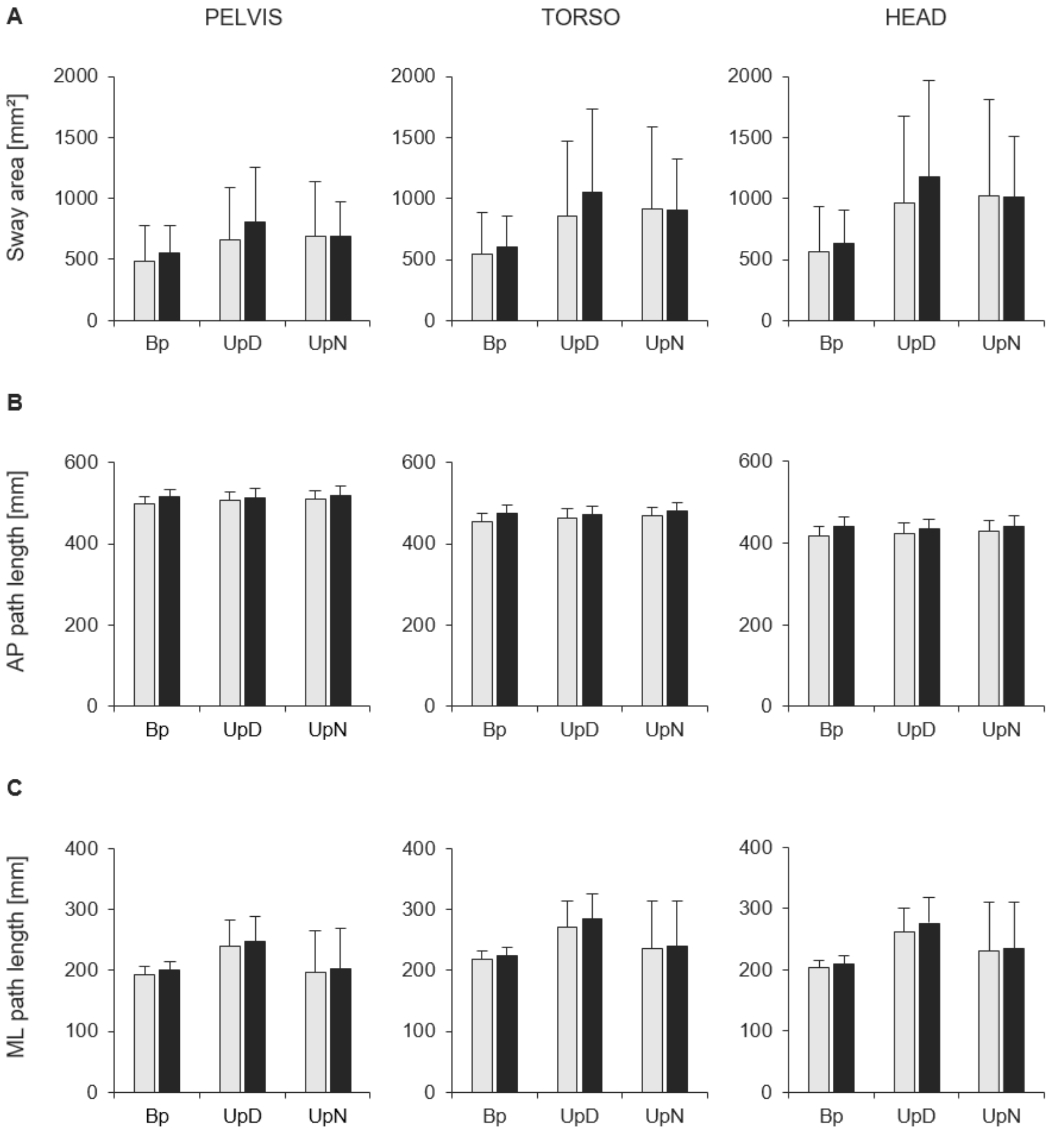


Figure 4.4 Kinematic variables of PELVIS, TORSO and HEAD for force-controlled biting (grey) and non-biting (black) during bipedal (Bp), unipedal dominant (UpD) and unipedal non-dominant stances (UpN). **A**, sway area; **B**, path length in anteroposterior direction (AP); **C**, path length in mediolateral direction (ML). All data are presented as mean ± $CI_{95\%}$.

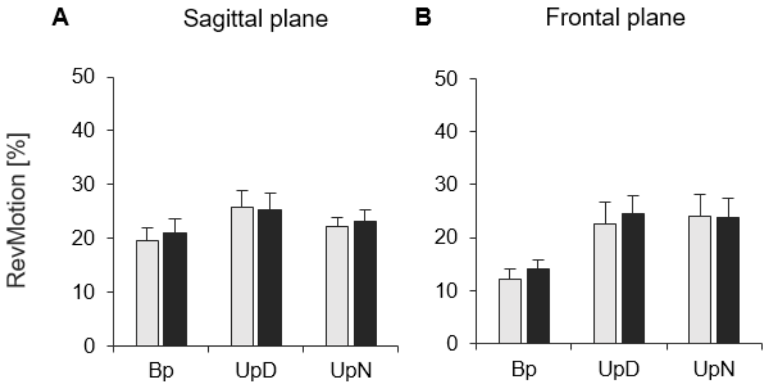


Figure 4.5 Percentage of time frames with reversed movement directions of PELVIS and TORSO (RevMotion) for force-controlled biting (grey) and non-biting (black) during bipedal (Bp), unipedal dominant (UpD) and unipedal non-dominant stances (UpN). **A**, RevMotion in sagittal plane; **B**, RevMotion in frontal plane. All data are presented as mean ± $CI_{95\%}$.

in sagittal plane [$p = 0.350$, $\eta_p^2 = 0.08$], but that in frontal plane significant main effect were apparent [$p = 0.044$, $\eta_p^2 = 0.032$]. Besides, significant main effects of support condition were found in both sagittal [$p = 0.001$, $\eta_p^2 = 0.49$] and frontal planes [$p < 0.001$, $\eta_p^2 = 0.69$], with *post hoc* Bonferroni corrections revealing significant lower percentages during Bp as compared to UpD [sagittal: $p = 0.006$; frontal: $p = 0.001$] and UpN [sagittal: $p = 0.049$; frontal: $p = 0.001$], respectively. On the other hand, RevMotion did not differ significantly between dominant and non-dominant legs, nor were there any interaction effects.

Joint kinematics

Mean angular velocities in frontal and sagittal planes for the three joints studied are presented in Figure 4.6. Table 4.4 reports the results of the hypothesis tests on these variables. With the exception of knee joint in frontal plane, FB significantly reduced AngVel in all joints and both planes under investigation. Furthermore, joint kinematics were significantly affected by support conditions. Bonferroni adjustments indicated that the differences between bipedal stance and dominant leg [all $p \leq 0.009$], and between bipedal stance and non-dominant leg [all $p \leq 0.001$] were statistically significant, but those between dominant and non-dominant legs were not.

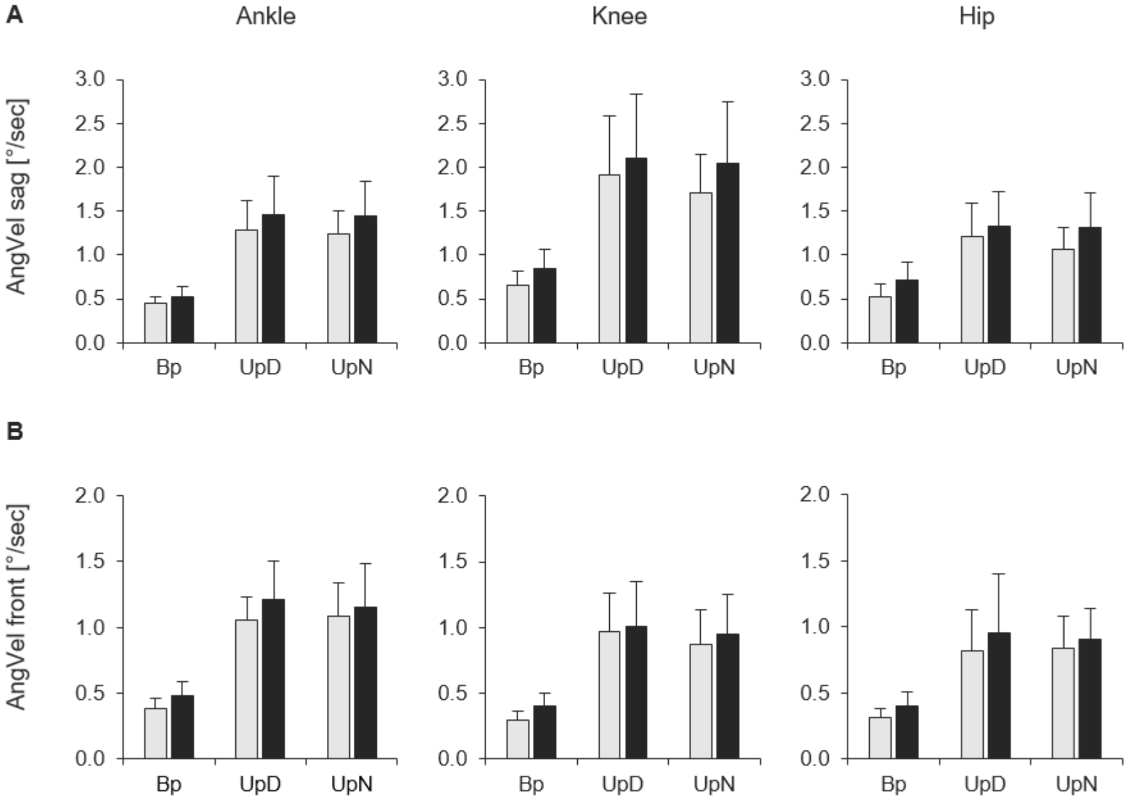


Figure 4.6 Mean angular velocities of ankle, knee and hip joints for force-controlled biting (grey) and non-biting (black) during bipedal (Bp), unipedal dominant (UpD) and unipedal non-dominant stances (UpN). **A**, sagittal plane (AngVel sag); **B**, frontal plane (AngVel front). All data are presented as mean ± $CI_{95\%}$.

Table 4.4 *P* values and effect sizes of joint kinematics for the different test conditions.

Variable	Joint	Oral motor task		Support condition		Interaction	
		p	η_p^2	*p*	η_p^2	*p*	η_p^2
AngVel sag [°/sec]	Ankle	0.008*	0.49	< 0.001*	0.74	0.229	0.13
	Knee	0.019*	0.41	< 0.001*	0.68	0.713	0.03
	Hip	0.005*	0.53	< 0.001*	0.74	0.566	0.05
AngVel front [°/sec]	Ankle	0.033*	0.35	< 0.001*	0.71	0.521	0.06
	Knee	0.057	0.29	< 0.001*	0.69	0.575	0.05
	Hip	0.013*	0.44	0.001*	0.60	0.607	0.04

AngVel = angular velocity; Sag = sagittal; Front = frontal.

P values and effect sizes (η_p^2) as revealed by two-way repeated measures ANOVA: * statistically significant; small effect: $\eta_p^2 = 0.01$; medium effect: $\eta_p^2 = 0.06$; large effect: $\eta_p^2 = 0.14$ (Cohen, 1992).

EMG

Figure 4.7 illustrates the results of EMG analyses on mean activity and VCoR. As indicated in Table 4.5, no main effect of oral motor tasks was found for mean EMG, whereas VCoR was significantly reduced during FB for three of the four muscle pairs. Muscular activity was also affected by support conditions. In particular, mean EMG of TA and GM was significantly lower in bipedal stance as compared to unipedal dominant [TA: p = 0.013; GM: p = 0.040] and unipedal non-dominant stances [TA: p = 0.001; GM: p = 0.023]. Furthermore, in bipedal stance VCoR of TA/SO was significantly less than on the non-dominant leg [p = 0.003], and VM/BF was significantly higher than on the dominant leg [p = 0.011]. Interaction effects were only apparent for VCoR of TA/GM, revealing increased influence of FB on the non-dominant leg.

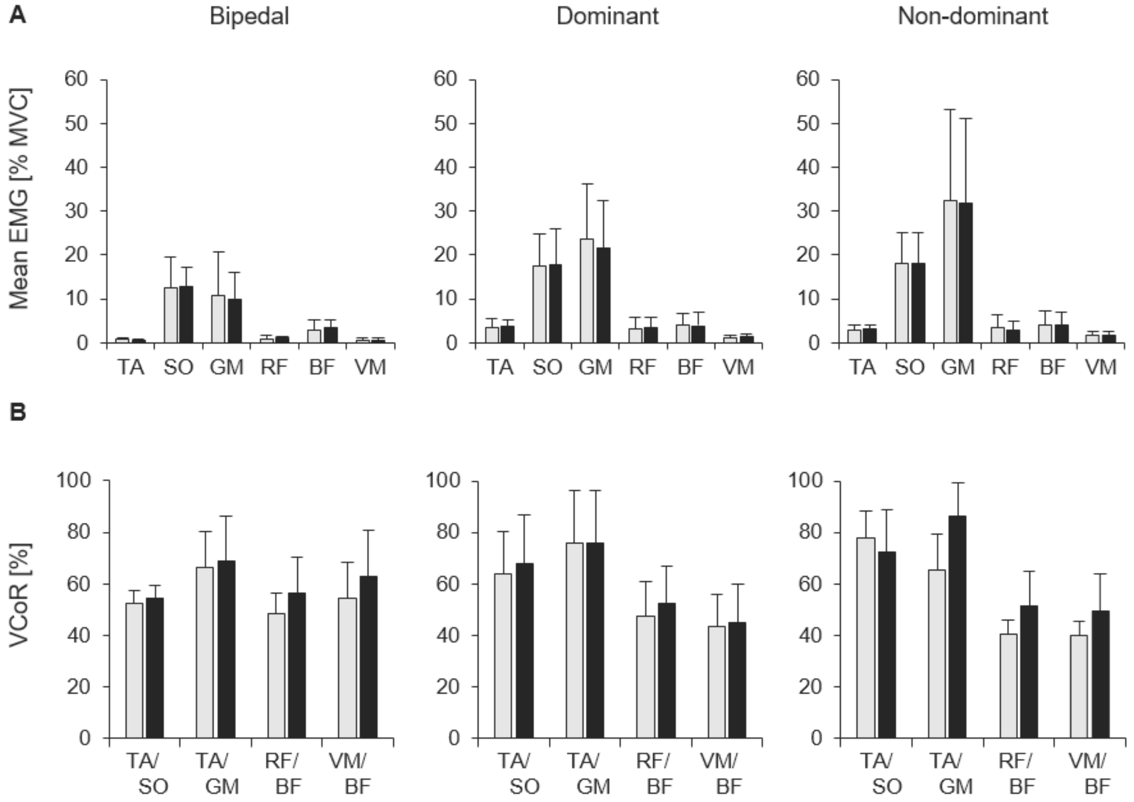


Figure 4.7 EMG measures of lower extremity muscles for force-controlled biting (grey) and non-biting (black) during bipedal, unipedal dominant and unipedal non-dominant stances. **A**, mean values of the normalized EMG; **B**, variability of muscular co-contraction ratios (VCoR). TA = tibialis anterior; SO = soleus; GM = gastrocnemius medialis; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris. All data are presented as mean ± $CI_{95\%}$.

Partial correlations

In a final step, partial correlations were applied to assess potential associations of CoP sway measures with RevMotion, joint kinematics and EMG data of the lower extremities. All combinations with the respective *r* values are listed in
Table **4.6**.

For RevMotion, partial correlations revealed no statistically significant correlations with CoP sway measures in bipedal stance, irrespective of the variable and plane considered. Contrastingly, in unipedal stance RevMotions correlated significantly with CoP sway area, and with CoP path lengths in the respective movement planes. The *r* values were medium to large, ranging between 0.329 and 0.622. Concerning associations with joint kinematics, descriptively, all correlations were positive, indicating a decrease in CoP displacements when joint motions were reduced. Statistically, CoP sway area correlated significantly with mean angular velocities of ankle, knee and hip joints in both sagittal and frontal planes. The *r* values entirely were large, irrespective of the stance considered, amounting 0.557 to 0.860. Significant positive correlations with mean angular velocities, moreover, were detected for AP and ML path lengths; merely in bipedal stance ankle AngVel in frontal plane did not significantly correlate with ML path length. The *r* values

Table 4.5 *P* values and effect sizes of EMG data for the different test conditions.

Variable	Muscle(s)	Oral motor task		Support condition		Interaction	
		p	η_p^2	p	η_p^2	p	η_p^2
Mean EMG [% MVC]	TA	0.513	0.04	0.001*	0.49	0.531	0.06
	SO	0.339	0.08	0.057	0.23	0.870	0.01
	GM	0.231	0.13	0.003*	0.41	0.572	0.04
	RF	0.717	0.01	0.056	0.23	0.354	0.09
	VM	0.337	0.08	0.063	0.26	0.806	0.02
	BF	0.697	0.01	0.812	0.02	0.628	0.04
VCoR [%]	TA / SO	0.941	0.01	0.019*	0.36	0.308	0.10
	TA / GM	0.013*	0.44	0.437	0.07	0.004*	0.39
	RF / BF	0.018*	0.41	0.461	0.07	0.662	0.04
	VM / BF	0.039*	0.33	0.006*	0.37	0.287	0.11

VCoR = variability of muscular co-contraction ratios; TA = tibialis anterior; SO = soleus; GM = gastrocnemius medialis; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris.

P values and effect sizes (η_p^2) as revealed by two-way repeated measures ANOVA: * statistically significant; small effect: $\eta_p^2 = 0.01$; medium effect: $\eta_p^2 = 0.06$; large effect: $\eta_p^2 = 0.14$ (Cohen, 1992).

Table 4.6 Partial correlations of CoP measures with RevMotion, joint kinematics, and EMG data.

Variable	Reference	Sway area		AP path length		ML path length	
		Bipedal	Unipedal	Bipedal	Unipedal	Bipedal	Unipedal
RevMotion	Sagittal	0.050	0.378*	0.037	0.329*	–	–
	Frontal	0.105	0.622*	–	–	-0.117	0.430*
AngVel sag	Ankle	0.761*	0.860*	0.728*	0.806*	–	–
	Knee	0.681*	0.797*	0.779*	0.826*	–	–
	Hip	0.665*	0.830*	0.577*	0.841*	–	–
AngVel front	Ankle	0.557*	0.695*	–	–	0.389	0.525*
	Knee	0.796*	0.709*	–	–	0.604*	0.736*
	Hip	0.653*	0.855*	–	–	0.775*	0.675*
Mean EMG	TA	-0.039	0.405*	0.297	0.386*	-0.192	0.223
	SO	0.087	-0.047	0.240	-0.134	-0.232	-0.397*
	GM	-0.033	-0.020	-0.239	-0.048	-0.164	-0.184
	RF	0.271	0.735*	-0.177	0.647*	-0.185	0.361*
	VM	-0.068	0.541*	-0.221	0.586*	-0.471*	0.368*
	BF	-0.130	-0.123	-0.256	-0.191	-0.299	-0.080
VCoR	TA / SO	0.232	0.243	0.297	0.115	0.086	-0.108
	TA / GM	0.290	0.283	-0.040	0.191	0.291	0.123
	RF / BF	0.271	0.556*	0.538*	0.328*	0.092	0.051
	VM / BF	0.453*	0.191	0.479*	-0.065	0.263	-0.275

AP = anteroposterior; ML = mediolateral; RevMotion = Percentage of time frames with reversed movement directions of PELVIS and TORSO; AngVel sag = angular velocity in sagittal plane; AngVel front = angular velocity in frontal plane; TA = tibialis anterior; SO = soleus; GM = gastrocnemius medialis; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; VCoR = variability of muscular co-contraction ratios.
Correlation coefficient *r* as revealed by partial correlations: * statistically significant; small correlation: $r = 0.10$; medium correlation: $r = 0.30$; large correlation: $r = 0.50$ (Cohen, 1988).

of CoP path lengths with mean angular velocities predominantly were large, ranging between 0.389 and 0.841. The highest correlation coefficients were recorded in conjunction with AP path length, especially in unipedal stance. Thereby, correlation coefficients in sagittal generally exceeded those in frontal plane. Furthermore, *r* values for ankle angular velocity tended to increase from frontal to sagittal plane, whereas those for the hip joint enlarged from bipedal to unipedal stance.

With regard to EMG data, statistically significant associations with CoP measures primarily were detected in unipedal stance. More precisely, correlation for mean EMG of RF and VM reached statistical significance, with *r* values ranging from 0.361 to 0.735. Statistically significant correlations between EMG data and CoP measures, moreover, were found for mean EMG of TA with CoP sway area and AP path length; each in unipedal stance. Additionally, significant negative associations with ML path length were obtained for mean EMG of SO in unipedal stance, and of VM in bipedal stance, respectively. Latter correlations were only medium, however. The analyses finally revealed that CoP measures also showed significant positive associations with VCoR values. Specifically, VCoR of RF/BF correlated significantly with AP path length in bipedal and unipedal stances, as well as with sway area in bipedal stance. In bipedal stance, both CoP measures additionally correlated with VCoR of VM/BF. Those correlations entirely were positive and *r* values ranged between 0.328 and 0.556.

4.5 Discussion

The purpose of this study was to investigate the effects of submaximal biting on postural control during bipedal narrow stance and single-leg stance by means of posturographic, kinematic and EMG analyses. It was hypothesized that FB significantly reduces postural sway concomitant with decreased oscillations of the trunk and head. These reductions were suggested to be accompanied by modulations in joint kinematics and patterns of muscular co-contractions, interrelated with changes in postural control strategies.

The study showed that biting at a submaximal force significantly decreased postural sway in terms of reduced CoP displacements. Both CoP sway area and CoP path length in AP and ML directions were significantly smaller than for NB. These sway reductions were independent of support condition, which was confirmed by the absence of any interaction effect. Submaximal biting also reduced trunk and head oscillations, as was apparent from decreased AP and ML path lengths of PELVIS, TORSO, and HEAD. These stabilizing effects were accompanied by lower mean angular velocities in ankle, knee and hip joints in both frontal and sagittal planes, as well as decreased muscular co-contraction variability in three of four muscle pairs. For all data – CoP measures (η_p^2 = 0.27–0.53), trunk and head kinematics (η_p^2 = 0.12–0.53), AngVel (η_p^2 = 0.29–0.53), and VCoR values

($\eta_p^2 = 0.33$–0.44) – biting predominantly had large effects, approximately as large as support effects. Hence, the effect of FB can be interpreted as substantial.

The observed significant sway reductions are in agreement with the findings of previous studies (Sforza et al., 2006; Sakaguchi et al., 2007; Hellmann et al., 2011c). The results, therefore, reveal that force-controlled oral motor activity not only alters postural control during normal stance but also during more demanding tasks, i.e., single-leg stance. However, the effect of FB was not as high as in the study of Hellmann et al. (2011c). This could indicate that the effect of oral motor activity on postural sway is less pronounced during more demanding balancing tasks. The relative positions of the CoP, and of PELVIS, TORSO, and HEAD were not statistically different among the experimental conditions, however, for either the AP or the ML positions. Thus, we could not confirm the anterior shift of the CoP found in a previous study (Hellmann et al., 2011c). The hypothesized stiffening effects caused by changes of single myofascial chains under the effect of craniomandibular muscle activity (Carson & Riek, 2001; Hellmann et al., 2011c) do not, therefore, seem entirely convincing.

As FB evoked systematic alterations of all segments’ path lengths, one could hypothesize that decreased postural sway during isometric masticatory activity might have been caused by an enhanced ankle strategy. This assumption is refuted by the results for RevMotion, joint kinematics, and muscular activities, however. Specifically, the analyses revealed uniform reductions of hip, knee and ankle angular velocities, whereas mean EMG activities and RevMotions were not or not systematically affected by oral motor tasks. Therefore, submaximal biting obviously did not alter the basic postural control strategies or the muscular contributions of the major functional muscle groups involved (Hellmann et al., 2015). Besides, although the significant reductions in VCoR values indicate some alterations in muscular co-contraction patterns, the estimates for the partial correlations including CoP measures and VCoR values primarily were not statistically significant. Therefore, the reductions in postural and kinematic sway yielded from FB apparently were not induced by the observed alterations in muscular co-contraction variability, which also questions the rationale behind this parameter to explain modulation of postural stability.

Instead, the reduced CoP, trunk and head oscillations could be attributed to the facilitating effects of submaximal biting (Boroojerdi et al., 2000), suggesting a neural coupling of the CMS to the postural control system. Miyahara et al. (1996) and Takada et al. (2000) showed that voluntary clenching of the teeth resulted in non-reciprocal facilitation of the ankle extensor and flexor muscles and attenuated reciprocal Ia inhibition from the pretibial to the soleus muscles. Based on the present results in conjunction with latter reports, modulation of motor system excitability (Boroojerdi et al., 2000) might have evoked an improved kinematic precision among the neuromuscular control strategies, resulting in lower mean angular velocities, which in turn led to decreased CoP displacements and, as a consequence, stabilization of trunk and head oscillations.

In addition to the effects of biting, significant differences between the support conditions were observed. As might be expected, CoP displacements in unipedal stance were significantly larger than for standing on both legs. The increased CoP sway area and CoP path length in ML direction are obviously attributable to the increased instability due to the smaller BoS; especially as, during single-leg support, ML fluctuations cannot be sufficiently controlled by the more precise ankle strategy or simple load–unload mechanisms, but rather by the gross movers of the hip. This enhanced reliance on the hip strategy during single-leg stance is emphasized by the RevMotion values in the frontal plane showing a higher percentage of hip strategy during unipedal as compared to bipedal stance. While the larger CoP sway area and ML path length seem consistent, narrowing of the BoS in the frontal plane also increased the CoP path length in the sagittal plane. With regard to the findings of Gribble & Hertel (2004a; 2004b), and Miller & Bird (1976), one explanation could be that in bipedal stance, the more subtle plantar and dorsi flexors of the ankle control posture, whereas in single-leg stance, AP neuromuscular control is primarily based on gross movements of the hip.

Notwithstanding the fact that the significant increase in the mean EMG of the plantar and dorsi flexors – particularly of tibialis anterior and gastrocnemius medialis – and the systematic alterations of AngVel for both ankle and hip joints might refute latter assumption, it must be noted that this study did not assess the activity of the muscles encompassing the hip, limiting the significance of any conclusions based on the present EMG or kinematic data. But when considering the RevMotion values in sagittal plane, it can be assumed that AP sway in single-leg stance is still primarily controlled by the ankle strategy, but that the impact of the muscles surrounding the hip joint tends to increase as the size of the BoS decreases. Latter conclusions are further confirmed by the partial correlations, demonstrating a shift between bipedal and unipedal stances with respect to best correlation coefficients. That is, whereas in bipedal narrow stance CoP sway area and CoP path length in AP direction are more closely correlated with AngVel sag of the ankle joint, latter sway variables in unipedal stances have been revealed to be similarly correlated with AngVel sag of the hip joint and ankle joint. Besides the joint kinematics, it is obvious that the higher coordinative demands as well as the relatively greater forces acting in single-leg stance require an increased demand for ipsilateral torque generation, and therefore, an augmented muscle activity to provide the necessary stability (Hellmann et al., 2015). Apart from that, none of the variables was significantly different for the dominant and non-dominant legs, which is consistent with latest reports (Scoppa et al., 2013).

In addition, partial correlation coefficients showed that in sagittal plane CoP displacements were more strongly associated with AngVel of the ankle joint, while in frontal plane CoP displacements were more strongly related to AngVel of the hip joint. These results are well in line with the general and widespread opinion that postural sway in AP direction as well as on stable and large support surfaces is primarily controlled by ankle muscles, whereas postural sway in ML direction as well as on unstable and narrow surfaces is primarily controlled by hip muscles in terms of the hip strategy (Winter, 1995; Winter, 2009; Macpherson & Horak, 2013). Interestingly, CoP sway measures were also highly related to AngVel of the knee joint and to the mean EMG of RF and VM, muscle groups surrounding the knee joint. Therefore, it is indicated that, in addition to the ankle and hip strategy, angular motions about the knee joint might play a key role in balance control as well.

One limitation of our study that should be considered is the short-term exposure of 10 s, which can neither simulate long-lasting effects of biting nor fulfil recommendations for posturographic assessments (≥25 s) (Parreira et al., 2013). The duration of measurement was restricted by the effort of the isometric masticatory contractions, however. Notwithstanding this, Parreira et al. (2013) recently pointed out that durations ≥ 10 s are sufficient to enable differences between postural control to be distinguished. Another limitation might be the lack of active controls, such as those used by Miyahara et al. (1996). These authors showed that both voluntary clenching of the teeth and contraction of upper limb muscles increased the amplitude of the soleus H-reflex, with increases during teeth clenching being greater than those induced by contraction of upper limb muscles (Miyahara et al., 1996). We suggest, therefore, that similar or smaller effects would have been observed among active controls. Further studies in which the stabilizing effects of FB are compared with submaximal clenching of the fists should, nevertheless, be conducted.

As the main result of our study, it may be emphasized that biting at a submaximal level significantly reduced postural sway in unipedal and bipedal narrow stance. This not only displays the stabilizing effect of oral motor tasks under more complex conditions but also provides additional evidence of the functional coupling of the CMS and human posture. The question of whether the coupling is mechanical or neural remains unanswered, however (Manfredini et al., 2012). The present study, moreover, showed for the first time that the sway reductions of the CoP during FB were accompanied by reduced trunk and head oscillations as well as by decreased joint motions in the lower extremities concomitant with alteration in muscular co-contraction patterns. However, as the statistical analyses revealed no change of the balance control strategy (RevMotion) and no significant association of CoP sway measures with muscular co-contraction variability, it is hypothesized that the reductions in postural and kinematic sway are attributable to an increased kinematic precision among the neuromuscular control patterns and/or enhanced stiffness of the trunk, but without changing the basic control strategies of postural control (Hellmann et al., 2015). Latter assumptions cannot be confirmed or rejected in detail on the basis of the current data, however.

Finally, it should be mentioned that all these effects were measured in healthy subjects, so even if there is evidence of comorbidity of masticatory, neck and lower-back-muscle pain (Wijer et al., 1996; Laat et al., 1998; Ciancaglini et al., 1999; Visscher et al., 2001), no conclusions about pathophysiological interactions can be drawn on the basis of these findings (Hellmann et al., 2011c; Manfredini et al., 2012). These physiological responses to isometric activation of the masticatory muscles suggest, nevertheless, that oral motor activity could be a strategy for the elderly or for patients with compromised postural control, for example to reduce the risk of falls.

5 General Modulation of Postural Sway during Concurrent Clenching

Published as

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5.1 Abstract

Recent studies reported on the potential benefits of submaximal clenching of the jaw on human postural control in upright unperturbed stance. However, it remained unclear whether these effects could also be observed among active controls. The purpose of the present study, therefore, was to comparatively examine the influence of concurrent muscle activation in terms of submaximal clenching of the jaw and submaximal clenching of the fists on postural sway. Posturographic analyses were conducted with 17 healthy young adults on firm and foam surfaces while either clenching the jaw (JAW) or clenching the fists (FIST), whereas habitual standing served as the control condition (CON). Both submaximal tasks were performed at 25% maximum voluntary contraction, assessed and visualized in real time by means of electromyography. Statistical analyses revealed that center of pressure (CoP) displacements were significantly reduced during JAW and FIST, but with no differences between both concurrent clenching activities. Further, a significant increase in CoP displacements was observed for the foam as compared to the firm condition. The results showed that concurrent muscle activation significantly improved postural sway compared with habitual standing, and thus emphasize the beneficial effects of jaw and fist clenching for static postural control. It is suggested that concurrent activities contribute to the facilitation of human motor excitability, finally increasing the neural drive to the distal muscles. Future studies should evaluate whether elderly or patients with compromised postural control might benefit from these physiological responses, e.g., in the form of a reduced risk of falling.

5.2 Introduction

Recently, submaximal clenching of the jaw was reported to significantly improve postural control and to decrease the sway of cranial body segments in upright unperturbed stance (Hellmann et al., 2011c; Hellmann et al., 2015; Ringhof et al., 2015c). The authors concluded that these improvements were induced by modulation of somatosensory input, particularly of the neck muscles (Abrahams, 1977), and facilitation of ankle extensor and flexor muscles (Miyahara et al., 1996; Takada et al., 2000) combined with attenuated reciprocal Ia inhibition (Takada et al., 2000). Neuroanatomical connections and projections of the trigeminal nerve to structures associated with postural control (Ruggiero et al., 1981; Buisseret-Delmas et al., 1999; Devoize et al., 2010) are thought to form the basis for these effects (Hellmann et al., 2011c; Ringhof et al., 2015c).

One limitation of the abovementioned studies (Hellmann et al., 2011c; Hellmann et al., 2015; Ringhof et al., 2015c), however, is the lack of active controls, as used by Miyahara et al. (1996). The authors reported that soleus H-reflex was not only increased by voluntary clenching of the teeth but also by isometric contraction of the wrist extensors or by clenching of the fists. Ringhof et al. (2015c), hence, suggested that sway reductions might also be observed among active controls. The purpose of this study, therefore, was to comparatively examine postural sway while submaximal clenching of the jaw and the fists. It was hypothesized that both concurrent muscular activities would significantly reduce postural sway compared with habitual standing, but with no differences between jaw and fist clenching. Moreover, this study examined the effects of concurrent muscle activation under more complex conditions, specifically on foam surfaces, i.e., when the proprioceptive system is challenged.

5.3 Material and methods

5.3.1 Subjects

A total of 17 healthy young adults participated in this study (Table 5.1). All subjects were naïve to the experimental procedure and had no known muscular or neurological diseases. The test protocol was approved by the Institutional Review Board, and written informed consent was given by all subjects.

5.3.2 Measurements

To specify the impact of force-controlled biting on postural sway, submaximal clenching of the jaw (JAW) was compared to submaximal clenching of the fists (FIST), both performed at muscular activities of 25% maximum voluntary contraction (MVC). To control for this, electromyographic (EMG) activity of the musculus masseter and the musculus flexor carpi radialis was recorded by use of bipolar surface electrodes (Ag/AgCl) and telemetric equipment (Noraxon; 1,000 Hz). A visual feedback of the rectified, smoothed (100 points moving median), and MVC-scaled EMG data was presented to the participants in real time. JAW was performed using a fluid self-adjusting intra-oral splint (Aqualizer), enabling an auto-balanced static equilibrium of the craniomandibular system. Simultaneously, the subjects were instructed to keep their fists in a relaxed resting position, and vice versa the mandible during FIST.

For the assessment of postural sway, time series of the center of pressure (CoP) were recorded by use of a force plate (AMTI; 1,000 Hz). Data were acquired for 30 s on stable and unstable surfaces. In stable conditions, subjects stood directly on the firm surface of the force plate, whereas in unstable conditions a foam balance pad (Airex) covered the force plate. Irrespective of the support surface, the subjects stood barefoot, on both legs, with the medial sides of the feet touching each other. The subjects were instructed to maintain an upright position, with their arms hanging at their sides, and to remain as stable as possible, focusing the feedback screen. In habitual standing, which served as the control condition (CON), the subjects focused a circular area attached to the wall. Feedback screen and circular area were positioned at eye level 3.0 m in front of the subjects.

The sequences of balance tasks and concurrent muscular activities were assigned randomly to the subjects. After familiarization, all subjects completed five trials per test condition.

Table 5.1 Subject characteristics.

Subjects [n]	Sex [m/f]	Age [years]	Height [m]	Mass [kg]	BMI [kg/m²]
17	8 / 9	22.4 ± 1.0	1.70 ± 0.04	67.7 ± 5.3	23.1 ± 0.9

All data are presented as mean ± $CI_{95\%}$.
BMI = body mass index.

5.3.3 Data analysis

The raw CoP data were processed with MATLAB R2014a. Initially, the CoP time series were filtered by use of a fourth-order Butterworth low-pass filter (cut-off frequency 10 Hz). Postural sway was then quantified by the area of the 95% confidence ellipse of the CoP (subsequently referred to as sway area), and CoP path lengths in anteroposterior (AP) and mediolateral (ML) directions.

5.3.4 Statistics

Statistical tests were performed by use of IBM SPSS Statistics 22.0. Kolmogorov-Smirnov and Mauchly's tests were conducted to confirm the normality and sphericity of data distribution, respectively. Differences in postural sway between concurrent muscle activation [JAW, FIST, CON] and support surfaces [firm, foam] were investigated by two-way repeated measures ANOVA, adjusted by use of Bonferroni corrections for multiple comparisons.

All data are presented as mean values and 95% confidence intervals (mean ± $CI_{95\%}$). Partial eta squared (η_p^2) is indicated to give information about effect sizes (Cohen, 1988; Richardson, 2011). The level of significance for all statistical tests was set a priori to $p = 0.05$.

5.4 Results

Statistical tests revealed significant main effects of concurrent muscle activation for both CoP sway area and CoP path lengths in AP and ML directions (Figure 5.1). Bonferroni adjustments indicated that each posturographic variable was significantly improved during JAW [sway area: $p = 0.044$; AP path length: $p < 0.001$; ML path length: $p = 0.003$] and FIST [sway area: $p = 0.024$; AP path length: $p < 0.001$; ML path length: $p = 0.001$] as compared to CON, but with no differences between JAW and FIST [sway area: $p = 1.000$; AP path length: $p = 1.000$; ML path length: $p = 0.802$]. Besides, significant main effects of support surfaces were indicated; with larger sway area and increased path lengths under foam conditions. All p values and effect sizes are listed in Table 5.2.

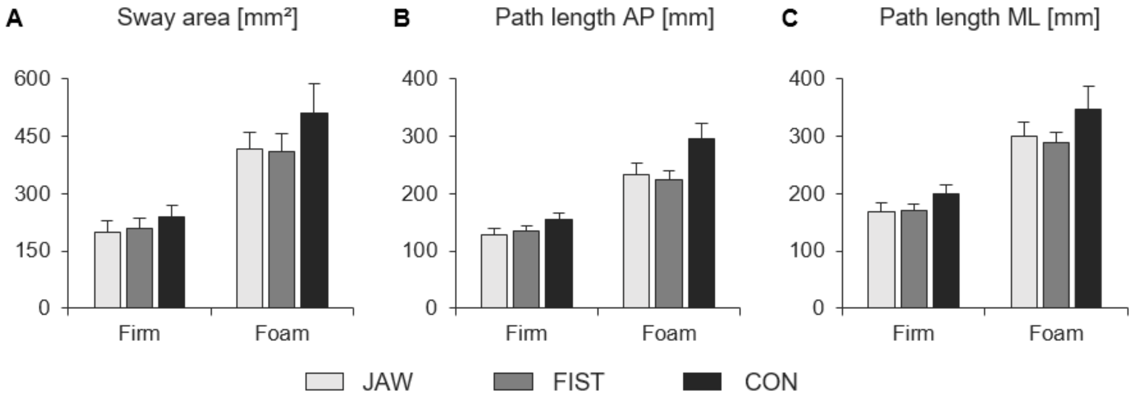

Figure 5.1 Postural sway on firm and foam surfaces as functions of concurrent muscle activities (JAW = jaw clenching; FIST = fist clenching; CON = habitual control condition). **A**, CoP sway area; **B**, CoP path length in anteroposterior direction; **C**, CoP path length in mediolateral direction. All data are presented as mean ± $CI_{95\%}$.

5.5 Discussion

The results showed that concurrent muscle activation, as submaximal jaw and fist clenching, significantly reduced postural sway in upright stance on firm and foam surfaces. By this means, the present follow-up study yields some additional findings, which should be highlighted below.

First, in Ringhof et al. (2015c) CoP displacements were reported to be less under submaximal biting as compared to a mandibular rest position, i.e., non-biting. Hence, the question remained whether these effects were the result of submaximal biting, in terms of decreased postural sway, or the result of non-biting, in terms of increased postural sway. The present study, however, showed that submaximal clenching of the jaw reduced CoP displacement compared with a habitual control condition, and thus emphasizes the beneficial effects of jaw clenching.

Second, this follow-up study demonstrated that postural sway is not only decreased on firm surfaces, but that submaximal jaw clenching also reduced postural sway on foam surfaces, i.e., under more demanding conditions. This reinforces the stabilizing effect of jaw motor activity, and provides additional evidence for the functional coupling of the craniomandibular system and human posture.

Table 5.2 *P* values and effect sizes of CoP measures for the different test conditions.

Variable	Concurrent activation		Support surface		Interaction	
	p	η_p^2	p	η_p^2	p	η_p^2
Sway area [mm²]	0.009*	0.32	< 0.001*	0.85	0.076	0.16
AP path length [mm]	< 0.001*	0.66	< 0.001*	0.95	< 0.001*	0.45
ML path length [mm]	< 0.001*	0.52	< 0.001*	0.91	0.109	0.14

AP = anteroposterior; ML = mediolateral.
P values and effect sizes (η_p^2) as revealed by two-way repeated measures ANOVA ($p < 0.05$): * statistically significant; small effect: $\eta_p^2 = 0.01$; medium effect: $\eta_p^2 = 0.06$; large effect: $\eta_p^2 = 0.14$ (Cohen, 1988; Richardson, 2011).

Finally, statistical analyses revealed that postural sway was not differently affected by submaximal clenching the jaw and submaximal clenching the fist, indicating that concurrent muscle activity of the m. masseter and the m. flexor carpi radialis similarly improved postural control. It is suggested that these motor activities contribute to the facilitation of human motor system excitability (Miyahara et al., 1996; Boroojerdi et al., 2000; Takada et al., 2000), which increases the neural drive to the distal muscles (Ebben, 2006; Ebben et al., 2008) in a manner similar to the Jendrassik maneuver (Jendrassik, 1885).

In conclusion, this study emphasizes the stabilizing effects of concurrent muscle activation in terms of submaximal jaw and fist clenching. These physiological responses to isometric activation of different muscle groups suggest that elderly or patients with compromised postural control might benefit from these concurrent activities, e.g., in the form of a reduced risk of falling.

6 Dynamic Postural Control during Voluntary Jaw Clenching

Extended version of the publication

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6.1 Abstract

Postural control is crucial for most tasks of daily living, delineating postural orientation and balance, with its main goal of fall prevention. Nevertheless, falls are common events, and have been associated with deficits in muscle strength and dynamic postural stability. Recent studies reported on improvements in rate of force development and static postural control evoked by jaw clenching activities, potentially induced by facilitation of human motor system excitability. However, there are no studies describing the effects on dynamic stability. The present study, therefore, aimed to investigate the effects of submaximal jaw clenching on recovery behavior from forward loss of balance, and potential associations with static postural stability. Participants were twelve healthy young adults, who were instructed to recover balance from a simulated forward fall by taking a single step while either biting at a submaximal force or keeping the mandible at rest. Bite forces were measured by means of hydrostatic splints, whereas a 3D motion capture system was used to analyze spatiotemporal parameters and joint angles, respectively. Additionally, dynamic stability was quantified by the extrapolated CoM concept, designed to determine postural stability in dynamic situations. Paired *t*-tests revealed that submaximal biting did not significantly influence recovery behavior with respect to any variable under investigation. Further, partial correlations indicated no significant associations between the dynamic stability measures and the static stability measures obtained in the first study. Therefore, reductions in postural sway evoked by submaximal biting are obviously not transferable to balance recovery as it was assessed in the present study. It is suggested that these contradictions are the result of different motor demands associated with the abovementioned tasks. Furthermore, ceiling effects and the sample size might be discussed as potential reasons for the absence of significances. Notwithstanding this, the present study also revealed that bite forces under both conditions significantly increased from subjects' release to touchdown of the recovery limb. Clenching the jaw, hence, seems to be part of a common physiological repertoire used to improve motor performance.

6.2 Introduction

Postural control is crucial for most activities of daily living, and comprises the neuromuscular control of postural orientation and postural equilibrium; the latter is commonly referred to as balance. Whereas postural orientation involves the positioning of the body's segments in space with respect to gravity, postural equilibrium delineates the ability to control the center of mass (CoM) within the base of support (BoS) (Woollacott & Shumway-Cook, 2002; Macpherson & Horak, 2013). The main function of the postural control system is to maintain stability, and thus to prevent any falls resulting from internal or external forces (Horak & Macpherson, 1996). However, due to the large variety of structures involved in this complex sensorimotor process, falls are common and serious events, potentially leading to severe injuries or even to death. Most of these falls occur during locomotion, such as tripping or slipping while walking (Blake et al., 1988). Investigations on postural control and fall related events, hence, are a particular issue of concern – for the scientific community, for the public health care system, and also for the fall-prone persons and patients themselves.

Do et al. (1982) were the first to introduce an experimental paradigm for assessing recovery behavior during forward loss of balance. This paradigm, in which subjects are suddenly released from a static forward lean angle, is still frequently used (Wojcik et al., 2001; Karamanidis & Arampatzis, 2007; Arampatzis et al., 2008; Karamanidis et al., 2008; Curtze et al., 2010; Barrett et al., 2012; Carty et al., 2012; Cheng et al., 2014; Graham et al., 2014), and has been shown to evince postural deficits in diverse populations. In this context, force potential of leg extensor muscles (Karamanidis et al., 2008), effective control of the whole body center of mass (Barrett et al., 2012), as well as step length and step velocity (Carty et al., 2012) have been identified as important variables for dynamic postural stability.

In recent years, several studies reported on the potential benefits of jaw clenching on human postural control. Thereby, a significant decrease in center of pressure (CoP) displacements induced by submaximal bite forces has been revealed by posturographic analyses (Hellmann et al., 2011c; Ringhof et al., 2015c). These reductions in postural sway were accompanied by decreased sway of cranial body segments (Ringhof et al., 2015c), systematic reductions in joint motions of the lower extremities as well as alterations in muscular co-contraction patterns (Hellmann et al., 2015). Modulation of somatosensory input, particularly for the neck muscles (Abrahams, 1977), and facilitation of human motor system excitability (Boroojerdi et al., 2000) were suggested to be the main causes for these improvements. In addition, facilitating effects on ankle extensor and flexor muscles (Miyahara et al., 1996; Takada et al., 2000) accompanied by attenuated reciprocal Ia inhibition from the pretibial muscles to the soleus muscle (Takada et al., 2000) might have contributed to the abovementioned stabilizing effects. Neuroanatomical connections and projections of the trigeminal nerve to structures associated with postural control (Ruggiero et al., 1981; Buisseret-Delmas et al., 1999; Devoize et al., 2010) are thought to form the basis for these findings.

Whereas the effects of jaw clenching on static postural control are merely consistent, there is no clear evidence as to whether dental occlusion in general affects postural sway; and also the mechanisms supporting this potential effect are still debated, and far from having reached a consensus (Cuccia & Caradonna, 2009; Michelotti et al., 2011; Manfredini et al., 2012). On the one hand, there are several studies in which significant sway reductions were observed, depending on the relative position of the mandible. Specifically, CoP displacements were found to be significantly decreased when the mandible was in symmetric centric relation as compared to intercuspal or lateral occlusion (Gangloff et al., 2000; Bracco et al., 2004; Sakaguchi et al., 2007).

Contradictory results are provided by Ferrario et al. (1996), reporting that postural sway was not significantly influenced by five dental positions, either in healthy women or in women with temporomandibular disorders and asymmetric malocclusion. Perinetti (2006; 2007) confirmed these findings in terms of non-significant differences between intercuspation and mandibular rest positions under eyes open and eyes closed conditions, disputing any relationship at the posturography level between dental occlusion and body sway. Some of this work has been criticized, however, primarily because of weak experimental designs and lack of control conditions. Moreover, in most of the publications, unfortunately, descriptions of the experimental design are inadequate. Some of the weak points are the lack of information concerning the generated bite forces and the mandibular positions during the experiments. In particular, when assessing the impact of dental occlusion on postural control, the actual oral motor activity mostly remained unknown. Furthermore, there is no international consensus about the definition of a physiological centric jaw relation (Keshvad & Winstanley, 2000). The common used phrase of symmetric positioning of the mandible in centric relation is, thus, not meaningful, and the jaw positions as experimental conditions are not comparable (Hellmann et al., 2015).

In conclusion, the contradictory reports merely are a consequence of diverse, potentially affecting experimental conditions and/or task instructions. The findings concerning the effects of jaw clenching on postural control are mostly consistent, however. Notwithstanding this, previous studies exclusively focused on the influence of force-controlled biting on postural sway under static conditions, i.e., upright unperturbed stance. To the best of the authors' knowledge, there are no reports describing the effects of jaw clenching on postural stability in dynamic situations; which is much more related to the risk of falling than static postural control (Rubenstein, 2006).

The purpose of this study, therefore, was to investigate the effects of submaximal jaw clenching on dynamic stability and lower extremity joint kinematics during balance recovery after forward loss of balance. This methodological approach comprises components of postural control, muscular strength and reaction time. As clenching of the jaw was shown to significantly improve reflex facilitation (Miyahara et al., 1996; Takada et al., 2000), static postural control (Hellmann et al., 2011c; Hellmann et al., 2015; Ringhof et al., 2015c), force production, and rate of force development (Forgione et al., 1991; Hiroshi, 2003; Ebben et al., 2008), it was hypothesized that submaximal biting would lead to improved balance recovery in terms of increased dynamic stability. We also hypothesized a decrease in joint flexion angles of the knee and hip of the recovery limb at touchdown as well as during the subsequent stance phase. Besides, it was assessed whether the participants' dynamic stability was interrelated with their static stability obtained within the study described in Chapter 4.

6.3 Material and methods

6.3.1 Subjects

Twelve healthy young adults, ten males and two females, with a mean age of 21.8 ± 1.8 years (height: 1.78 ± 0.04 m; mass: 72.85 ± 2.35 kg) participated in the study. All participants were naïve to the experiments, and presented with full dentition (except for 3rd molars) in neutral occlusion. None of them had any self-reported muscular or neurological diseases that could have affected their ability to perform the experiments. The study was approved by the Ethics Committee of the German Sport University Cologne (no. 38/12), and written informed consent was given by all subjects.

6.3.2 Experimental procedure

To evaluate the effects of jaw clenching on balance recovery, a crossover design was applied. The experimental design included a balance recovery task in the form of a simulated forward fall, and two oral motor tasks: force-controlled biting and non-biting. The order of oral motor tasks was counterbalanced across the subjects, i.e. half of the sample started with force-controlled biting, whereas the others first performed the non-biting control condition.

Oral motor tasks

Force-controlled biting (FB) was conducted at submaximal bite forces of 150 N, corresponding to mean individual maximum voluntary contraction of the masseter of 15.07 ± 4.47 %. This bite force is in accordance with previous experiments (Hellmann et al., 2011c), revealing that submaximal biting significantly affected postural sway in upright unperturbed stance. To monitor the bite forces, a hydrostatic system consisting of liquid-filled pads fixed to the maxilla was used. Biting on the pads resulted in increased hydrostatic pressure, which was presented to the subjects as numerical real-time feedback on a display positioned directly in front of them. Detailed information on the hydrostatic system and the oral splints can be obtained from Hellmann et al. (2011c) and Ringhof et al. (2015c).

In the non-biting control condition (NB) the oral device was worn as well, but the subjects were asked to keep their mandible in a resting position, that is consciously applying no bite force, and monitoring this condition by looking at the feedback screen.

Balance recovery task

Forward falls were simulated by an experimental approach that has been previously reported by Do et al. (1982), and Karamanidis & Arampatzis (2007). Within this test, subjects were instructed to attempt to recover balance by taking a rapid single step after being suddenly released from an inclined forward posture (Wojcik et al., 2001; Karamanidis et al., 2008).

In the present study, the forward-inclined position was attained by a horizontal cable that was attached to a safety harness worn by the subjects around the trunk. At the other end, the horizontal cable was connected to an electromagnetic system, which could be manually released by the investigators (Figure 6.1). To avoid any injuries resulting from falls, the safety harness additionally was attached to a ceiling-mounted rope, which prevented contact of any body part, other than the feet, with the ground (Karamanidis et al., 2008).

At the beginning of each trial, the subjects stood barefoot with both feet on a force plate (AMTI, model BP600900, 1,000 Hz; Advanced Mechanical Technology, Watertown, MA, USA), and were then moved in a forward-inclined position. The angle of this leaning position was individually adjusted for each subject within a pilot trial prior to the measurements. Thereby, the lean angle – defined as the angle between the vertical in the sagittal plane and the line connecting the CoM and the center of the ankle joint – was gradually increased until the subjects no longer felt able to recover balance by taking a single step. Once the lean angle was determined, this angle was maintained throughout all recovery trials. The mean angle of the forward lean was 36.15 ± 1.38°, evoking a mean horizontal force component of 29.65 ± 2.99 % of the subject's body weight; which is very similar to the loads used by Barrett et al. (2012), Carty et al. (2012), and Karamanidis et al. (2008).

In this position, with heels touching the ground and arms hanging at their sides, the subjects were asked to concurrently perform the oral motor tasks. The respective bite force had to be maintained for at least two seconds until the investigators randomly released the electromagnetic system within a timeframe of five seconds. Once the forward fall was initiated, the subjects were encouraged to restore balance by taking a rapid single step placing their recovery limb properly in front of their other limb. After one familiarization trial, for each test condition five trials were conducted.

6.3.3 Measurements

All data collected were simultaneously recorded by a Vicon motion capture system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK). As indicated above, bite forces were measured by means of a hydrostatic system, sampling at 1,000 Hz. Besides, kinematic data were captured by use of thirteen infrared cameras (Vicon MX camera system, 200 Hz) and thirty-nine passive reflective markers (diameter 14 mm). The reflective markers were placed on the subjects' skin in accordance with the Vicon Plug-In Gait full-body marker set. Based on this, mathematical human multibody models (Kadaba et al., 1990; Davis et al., 1991) allowed for the definition of rigid body segments and its CoM, and the calculation of kinematic parameters, such as joint angles.

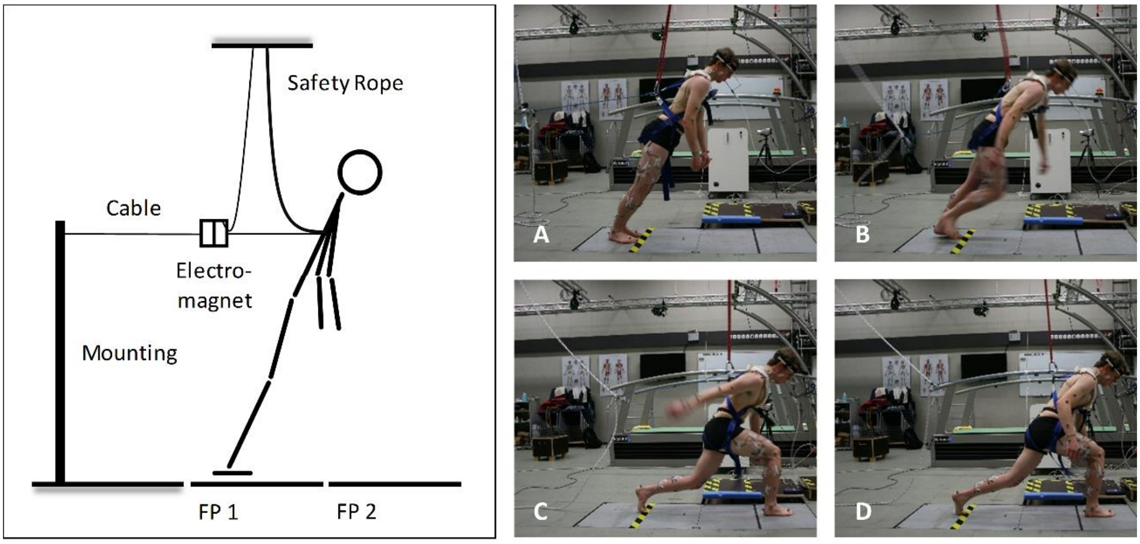

Figure 6.1 Schematic illustration of the experimental setup (left) and the analyzed time points (right) for assessing dynamic stability after forward loss of balance. **A**, release of the subject; **B**, toe-off from the ground of the recovery limb; **C**, touchdown of the recovery limb; **D**, 500 ms after touchdown. FP = force plate.

6.3.4 Data Analysis

As all participants were able to successfully recover balance with a single step, all five trials were included in the analyses, based on which mean values were calculated for each test condition. Hereto, data were processed using MATLAB R2014b (The MathWorks, Natick, MA, USA). Initially, the time series were filtered by use of a fourth-order Butterworth low-pass filter with a cut-off frequency of 8 Hz. To determine the potential effects of FB on balance recovery, thereafter, for each trial four time points were identified (Figure 6.1): release of the subject (*Release*, A), toe-off from the ground of the recovery limb (*Toe-Off*, B), touchdown of the recovery limb (*TD*, C), and 500 ms after touchdown (TD_{+500}, D) (Karamanidis et al., 2008). For time-normalized analyses, additionally two main phases of recovery were defined: the *Falling phase* covered the time interval from *Release* until *TD* (normalized from -100% to 0%), and the *Stance phase* involved the period between *TD* and TD_{+500} (normalized from 0% to 100%).

Spatiotemporal parameters

Based on the abovementioned time points, subjects' response time and duration of recovery were determined. The response time was considered as the time interval from *Release* until *Toe-Off*, and the duration of recovery was indicated by the time interval from *Release* until *TD*. Further, the step length, defined as the linear distance between the initial and final toe position in anteroposterior direction, was calculated.

Joint angles

Joint kinematics were analyzed in sagittal plane for the hip, knee, and ankle joints of the recovery limb. Specifically, mean joint angles at *TD* and maximum joint flexion angles (dorsiflexion angle in terms of the ankle joint) during the *Stance phase* were investigated.

Dynamic stability

Postural stability was quantified by the extrapolated CoM concept (Hof et al., 2005). This concept is based on the inverted pendulum model of balance and allows to determine postural stability in dynamic situations (Hof et al., 2005; Arampatzis et al., 2008; Hof, 2008; Curtze et al., 2010). Hereto, the margin of stability (MoS) in anteroposterior direction was calculated as it has been proposed by Hof et al. (2005):

$$MoS = pBoS - xCoM$$

in which $pBoS$ is the anterior boundary of the BoS (projection of the anteroposterior position of the toe from the recovery limb on the ground), and $xCoM$ is the extrapolated CoM in the anteroposterior direction. The extrapolated CoM in turn was calculated as follows:

$$xCoM = pCoM + \frac{vCoM}{\sqrt{g/l}}$$

where $pCoM$ is the anteroposterior component of the CoM (projection of the anteroposterior position of the CoM on the ground), $vCoM$ is the anteroposterior velocity of the CoM, g is the acceleration of gravity, and l is the distance between the CoM and the center of the ankle joint in the sagittal plane (Hof, 2008).

The extrapolated CoM concept suggests that postural stability in anteroposterior direction is maintained when the projection of the extrapolated CoM is located within the BoS, i.e. the MoS shows positive values (Hof et al., 2005; Karamanidis et al., 2008). A loss of dynamic stability in turn is indicated by negative values of the MoS, i.e. in cases where the extrapolated CoM exceeds the anterior boundary of the BoS. The moment the MoS changed from negative to positive values (subsequently referred to as Stability Point), therefore was depicted as the main outcome parameter. In addition, dynamic stability was calculated for the moments of TD and TD_{+500}, respectively.

6.3.5 Statistics

All statistical tests were performed by use of IBM SPSS Statistics 22.0 (IBM Corporation, Armonk, NY, USA). First, Kolmogorov-Smirnov tests were applied to confirm the normality of data distribution. Mauchly’s tests of sphericity were then conducted to determine whether the assumption of sphericity was violated. When this did occur, Greenhouse-Geisser estimates were used to correct for any violations.

Although the ordering was counterbalanced across the subjects, which minimized the likelihood of confounding, preliminary analyses were conducted to evaluate whether the order of exposure had an effect on the variables under investigation. However, repeated measures ANOVAs indicated that neither the order of presentation nor the trial number within both test conditions had been influential. Based on these assumptions, the effects of oral motor tasks on spatiotemporal parameters, joint angles, and dynamic stability were assessed by paired *t*-tests, separately run for each dependent variable under investigation. Further, one-sample *t*-tests were used to contrast the intended and actual bite forces at subjects' *Release* for both oral motor tasks and, by this means, to check whether the subjects met the requested oral motor tasks. Differences in bite forces between oral motor tasks [FB, NB] and between time points [*Release*, *TD*] were investigated by two-way repeated measures ANOVA. Statistical differences are reported by their level of significance, while effect sizes were determined using Cohen's d (small effect: $d = 0.20$; medium effect: $d = 0.50$; large effect $d = 0.80$) or partial eta squared (small effect: $\eta_p^2 = 0.01$; medium effect: $\eta_p^2 = 0.06$; large effect $\eta_p^2 = 0.14$) in case of *t*-tests and ANOVAs, respectively (Cohen, 1988; Richardson, 2011).

In a final step, partial correlations were used to detect potential associations of dynamic stability measures with the CoP displacements obtained in the first study (Chapter 2), whereat the effects of sex and oral motor tasks were removed throughout the tests. As the present study did not assess dynamic postural control in frontal plane and for stepping with the non-dominant leg, partial correlations were computed only for those variables covering anteroposterior motions as well as the dominant leg. Hence, whereas the Stability Point and the MoS values at *TD* and TD_{+500} were included as measures for dynamic postural stability, static postural stability was represented by the subjects' MoS_{min} and CoP path length in AP direction during single-leg stance on the dominant leg. Associations between the variables under investigation are reported by their correlation coefficient r. Values of $r = 0.10$ indicate small, $r = 0.30$ medium, and $r = 0.50$ large correlations (Cohen, 1988).

For all statistical tests, the level of significance was set to $p = 0.05$. The data are reported as mean values and 95% confidence intervals (mean ± $\text{CI}_{95\%}$).

6.4 Results

Bite forces

The time-normalized bite forces from *Release* until TD_{+500} are shown in Figure 6.2. Descriptively, bite forces under FB conditions increased from 150 N at *Release* to over 200 N at *Toe-Off*, with a subsequent decrease to baseline values. But, also in NB slight increases in bite force from *Release* to *Toe-Off* and to *TD* were observed.

Statistical tests revealed no significant deviations of the actual bite forces from the intended bite forces at *Release* [FB: $p = 0.515$; NB: $p = 0.056$], and thus confirmed the compliance with the oral motor tasks. On the other hand, significant main effects of oral motor tasks [$p < 0.001$, $\eta_p^2 = 0.97$] and time points [$p = 0.006$, $\eta_p^2 = 0.951$] were indicated by two-way repeated measures ANOVA. *Post-hoc* analysis (paired *t*-tests) revealed that bite forces were statistically higher under FB as compared to NB, both at *Release* [$t_{(11)} = 26.03$, $p < 0.001$, $d = 9.64$] and at *TD* [$t_{(11)} = 12.92$, $p < 0.001$, $d = 4.82$]. In addition, bite forces under both oral motor tasks significantly increased from *Release* to *TD* [FB: $t_{(11)} = 3.03$, $p = 0.011$, $d = 0.96$; NB: $t_{(11)} = 2.94$, $p = 0.014$, $d = 1.03$].

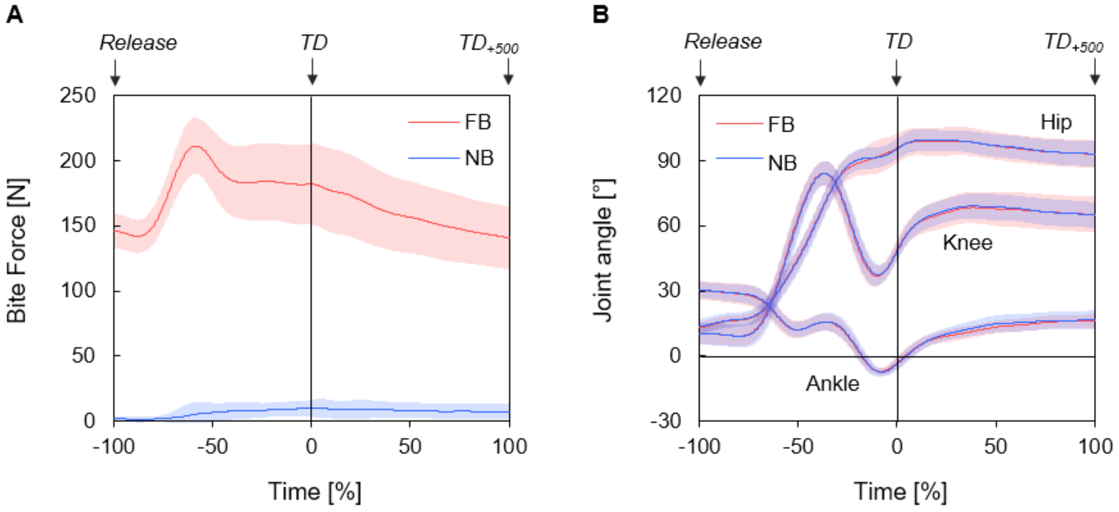

Figure 6.2 Time-normalized bite forces (**A**), and time-normalized joints angles of the hip, knee, and ankle joints in sagittal plane (**B**) during *Falling phase* and *Stance phase* as functions of oral motor tasks (FB = force-controlled biting; NB = non-biting). All data are presented as mean ± $CI_{95\%}$. *Falling phase*: from *Release* until touchdown (*TD*) (normalized from -100% to 0%); *Stance phase*: from *TD* until 500 ms after touchdown (TD_{+500}) (normalized from 0% to 100%).

Table 6.1 Spatiotemporal parameters as functions of oral motor tasks.

Variable	FB	NB	$t_{(11)}$	*p*	*d*
Response time [s]	0.162 ± 0.011	0.163 ± 0.013	0.30	0.770	0.05
Duration of recovery [s]	0.409 ± 0.019	0.414 ± 0.019	1.35	0.206	0.17
Step length [m]	1.086 ± 0.079	1.104 ± 0.080	1.70	0.118	0.15

All data are presented as mean ± $CI_{95\%}$.
FB = force-controlled biting; NB = non-biting.

Spatiotemporal parameters

The response time and the duration of recovery were both not significantly influenced by oral motor tasks. Moreover, there was no significant difference between the subjects' step length in the two testing conditions (Table 6.1).

Joint angles

The time-normalized joint angles of the hip, knee and ankle joints in the sagittal plane are illustrated in Figure 6.2. All joint angles at *TD* were statistically unaffected by oral motor tasks. Additionally, maximum joint flexion angles in *Stance phase* showed no significant differences between FB and NB (Table 6.2).

Table 6.2 Joint flexion angles at *TD* and maximum joint flexion angles during *Stance phase* as functions of oral motor tasks.

	Variable	FB	NB	$t_{(11)}$	*p*	*d*
TD	Ankle flexion [°]	-3.12 ± 2.98	-3.64 ± 2.90	0.89	0.395	0.11
	Knee flexion [°]	48.79 ± 4.77	48.06 ± 4.17	0.90	0.390	0.10
	Hip flexion [°]	95.68 ± 6.71	95.35 ± 4.71	0.20	0.849	0.04
Stance phase	Max. ankle flexion [°]	17.77 ± 2.71	18.24 ± 4.04	0.32	0.755	0.09
	Max. knee flexion [°]	69.96 ± 7.60	70.15 ± 5.82	0.14	0.892	0.02
	Max. hip flexion [°]	101.07 ± 6.31	101.52 ± 4.94	0.35	0.736	0.05

Negative values for ankle joint angle represent a dorsi flexion, and positive values indicate a plantar flexion, respectively. All data are presented as mean ± $CI_{95\%}$.
FB = force-controlled biting; NB = non-biting; TD = touchdown.

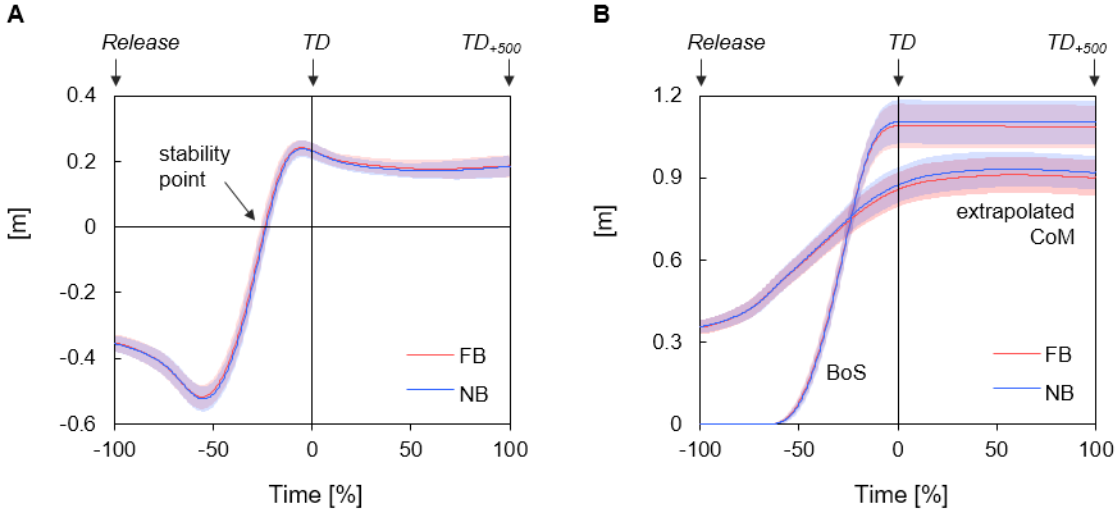

Figure 6.3 Time-normalized curves of the margin of stability (MoS, **A**), extrapolated center of mass (extrapolated CoM, **B**), and anterior boundary of the base of support (BoS, **B**) during *Falling phase* and *Stance phase* as functions of oral motor tasks (FB = force-controlled biting; NB = non-biting). All data are presented as mean ± $CI_{95\%}$.
Falling phase: from *Release* until touchdown (*TD*) (normalized from -100% to 0%); *Stance phase*: from *TD* until 500 ms after touchdown (TD_{+500}) (normalized from 0% to 100%); Stability Point: time point the MoS changes from negative to positive values.

Dynamic stability

Figure 6.3 shows the time-normalized data of the MoS, the extrapolated CoM, and the anterior boundary of the BoS. The Stability Point was obtained at -23.88 ± 2.33 % and -23.22 ± 2.21 % of the falling phase for FB and NB, respectively. In particular, paired *t*-test indicated no significant difference in this point between testing conditions [$t_{(11)}$ = 1.48, p = 0.168, d = 0.19]. Further, FB did not significantly affect the anterior boundary of the BoS, the anteroposterior component and velocity of the CoM, the extrapolated CoM, and the MoS; neither at *TD* nor at TD_{+500} (Table 6.3).

Partial correlations between static and dynamic stability

In a final step, partial correlations were computed to investigate whether there is an interrelation between the participants' static and dynamic stability. Hereto, MoS_{min} and CoP path length in AP direction, which were obtained within the first study (Chapter 4), were correlated with the Stability Points and the MoS values at *TD* and TD_{+500} of the present

Table 6.3 Stability parameters at *TD* and TD_{+500} as functions of oral motor tasks.

	Variable	FB	NB	$t_{(11)}$	*p*	*d*
TD	BoS [m]	1.090 ± 0.080	1.105 ± 0.080	1.44	0.177	0.12
	Position CoM [m]	0.731 ± 0.053	0.742 ± 0.054	1.63	0.131	0.14
	Velocity CoM [m/s]	0.501 ± 0.056	0.521 ± 0.059	1.59	0.141	0.23
	Extrapolated CoM [m]	0.857 ± 0.063	0.874 ± 0.065	1.80	0.100	0.17
	MoS [m]	0.234 ± 0.024	0.231 ± 0.025	0.39	0.701	0.06
TD_{+500}	BoS [m]	1.086 ± 0.079	1.104 ±0.080	1.70	0.118	0.15
	Position CoM [m]	0.902 ± 0.065	0.922 ± 0.062	1.12	0.286	0.20
	Velocity CoM [m/s]	-0.010 ± 0.018	-0.012 ± 0.021	0.20	0.842	0.08
	Extrapolated CoM [m]	0.902 ± 0.065	0.922 ± 0.062	1.12	0.286	0.20
	MoS [m]	0.184 ± 0.030	0.182 ± 0.028	0.13	0.900	0.03

All data are presented as mean ± $CI_{95\%}$.
FB = force-controlled biting; NB = non-biting; *TD* = touchdown; TD_{+500} = 500 ms after touchdown; BoS = anterior boundary of the base of support; CoM = center of mass; MoS = margin of stability.

study. The respective correlation coefficients and *p* values can be obtained from Figure 6.4. Statistics revealed that none of the dynamic stability measures correlated significantly with MoS_{min} or CoP path length in AP direction. Further, partial correlation coefficients merely were small to medium, ranging from 0.003 to 0.336. Therefore, it is indicated that static and dynamic postural stability are not associated with each other.

6.5 Discussion

The aim of the present study was to examine the effects of submaximal jaw clenching on dynamic postural stability and joint kinematics during balance recovery after forward loss of balance. We hypothesized that force-controlled biting would lead to improved balance recovery in terms of increased dynamic stability and lower joint flexion angles of the knee and hip at touchdown and during the subsequent stance phase.

The results, however, showed that biting at a submaximal force did not significantly influence recovery behavior of healthy young adults with regard to the variables under investigation, and furthermore, that participants' dynamic stability was not associated with their static stability. Therefore, the present study indicates that the reductions in postural sway evoked by submaximal biting are obviously not transferable to balance recovery as it was assessed in the present study.

Previous studies on the impact of concurrent jaw clenching activities observed significant improvements in peak force and rate of force development as compared to non-clenching controls (Forgione et al., 1991; Hiroshi, 2003; Ebben et al., 2008). Further, significant reductions in CoP displacements have been described under static conditions (Hellmann et al., 2011c; Ringhof et al., 2015c). To the authors' knowledge, this study was the first to examine the effects of oral motor activities on dynamic postural stability in general, and specifically on balance recovery from forward loss of balance. Nevertheless, the present data are very similar in magnitude to those of other studies on balance

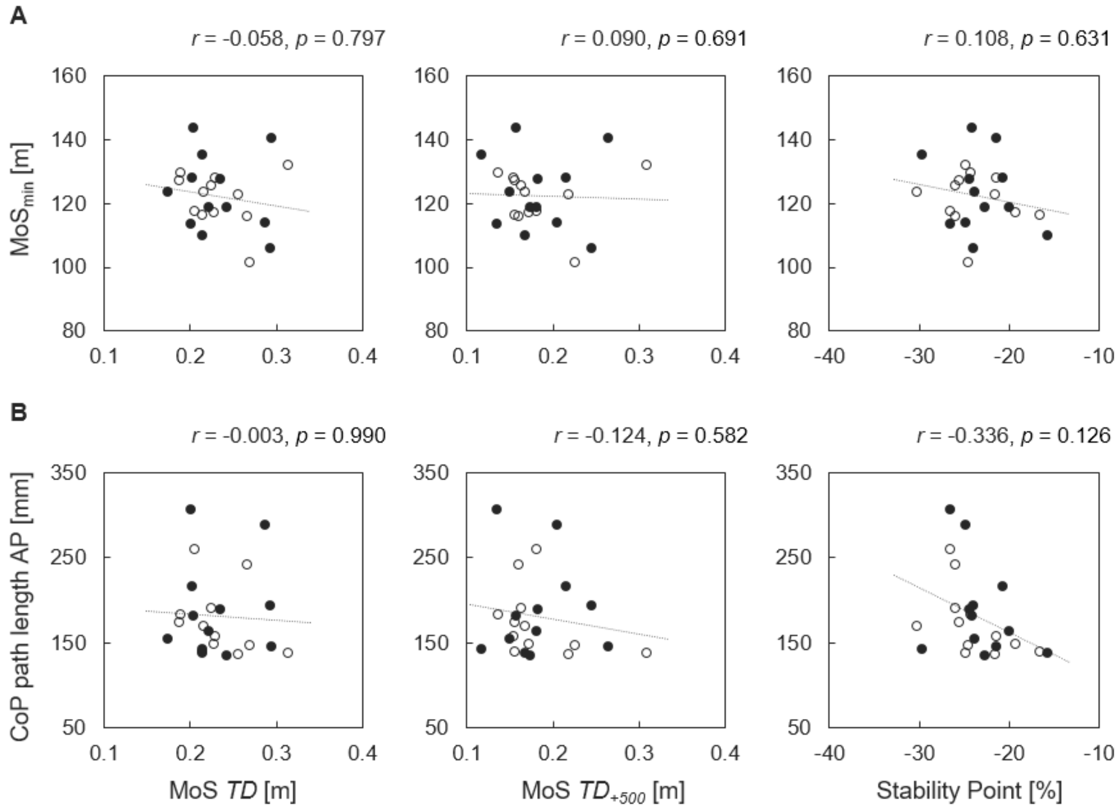

Figure 6.4 Scatter plots with partial correlation coefficients between measures of static and dynamic stability. **A**, minimum margin of stability ($\mathrm{MoS}_{\mathrm{min}}$); **B**, CoP path length in anteroposterior (AP) direction. MoS *TD* = margin of stability at touchdown; MoS TD_{+500} = margin of stability 500 ms after touchdown; Stability Point = time point the MoS changes from negative to positive values.

recovery (Karamanidis & Arampatzis, 2007; Karamanidis et al., 2008; Curtze et al., 2010). This forms the basis for the further discussion, enabling conclusive statements with regard to dynamic postural stability. In this context, the authors attempt to provide some explanations for the lack of observed differences; without any claim to be comprehensive.

First, the absence of any biting effects might be evoked by the different motor demands associated with static postural control compared with balance recovery after simulated forward falls. The former is primarily based on fine motor control relying on feedback mechanisms and unconscious and highly automated processes (Horak, 2006). Contrastingly, the latter requires gross motor coordination and huge demands on explosive muscle activation and force production (Karamanidis et al., 2008). Specifically, in the scenario of simulated forward falls, this process mainly follows feedforward control. Hence, the subjects can preselect their compensatory movements, which finally reduces the contribution of reflexes and automated processes. This distinction is of particular relevance, because most effects of jaw clenching activities were considered to be caused by facilitation of reflexes and motor system excitability (Miyahara et al., 1996; Boroojerdi et al., 2000; Takada et al., 2000). Modulation of somatosensory input, particularly for the neck muscles (Abrahams, 1977) during simulated forward falls might, thus, be not an issue.

In this context, one could speculate that more ecologically valid experiments, which are representative for the analysis of real falls, might have revealed differing results. As indicated above, in simulated forward falls, the subjects are well aware of the upcoming forward fall, which increases the proportion of voluntary movement control. In everyday life, however, the subjects are mostly unaware of such tripping or slipping events. The process of recovering stability, hence, mainly follows stereotypic movement patterns, initially provoked by stimulation of the muscle spindles in the calf muscles. Consequently, recovery is primary based on reflexes or automated compensatory movements, all requiring no or only little focused attention (Macpherson & Horak, 2013). Based on the findings on reflex facilitation (Miyahara et al., 1996; Takada et al., 2000), and concurrent activation potentiation (Ebben, 2006), we hypothesize that investigation on unexpected perturbations possibly would offer ergogenic effects for concurrent clenching activities, whereas the increase in voluntary movement control evoked by the chosen study design might have contributed to the absence of any significant alterations. Latter assumptions are further emphasized by the low to medium and statistically non-significant partial correlations, revealing no associations between static and dynamic postural control. Several previous studies obtained similar results regarding this matter. In particular, when contrasting CoP displacement during quite stance with measures of gait variability or dynamic stability after large perturbations rather weak correlations were observed (Shimada et al., 2003; Granacher et al., 2011a). A recent study by Giboin et al. (2015), furthermore, even found no transfer between very similar balance tasks. This is contradictory to former literature, which often treated balance as a general ability. Current research suggests that static and dynamic balance should rather be classified as highly task-specific sensorimotor skills (Giboin et al., 2015; Kummel et al., 2016), whereat the postural control system uses different mechanism to control balance (Granacher et al., 2011a).

On the other hand, the lack of observed differences in dynamic stability could be the result of a ceiling effect, whereby the perturbation for the given sample was not difficult enough. Subjects were young healthy adults, and all obtained very high stability values (MoS > 0.2 m at *TD*). Potentially, subjects with diminished postural control and/or reduced force potential as, e.g., elderly could benefit from force-controlled biting. This investigation cannot answer this question, however.

The final factor to be considered in the interpretation of the data is the bite force. At *Release* bite forces under both testing conditions were maintained at the intended level, confirming the compliance with the oral motor tasks. At *TD*, however, significant increases in bite forces for both oral motor tasks were observed. In terms of NB, the results imply that an open-mouth, non-clenching condition is an unphysiological state which is not preferred during challenging situations. This is reinforced additionally by the fact that the subjects, even when already submaximal clenching their jaw, significantly increased their bite force from 146.01 ± 13.04 N to more than 200 N at *Toe-Off*. Clenching the jaw, hence, seems to be part of a common physiological repertoire used to improve the neural drive to distal body segments and, by this means, to enhance performance in many ways (Ebben, 2006; Ringhof et al., 2015a). This, in turn, would suggest that many studies focusing the ergogenic effects of jaw clenching actually did not observe performance improvements when the jaw was clenched, but rather a decrease in the non-clenching condition (Hiroshi, 2003; Ebben et al., 2008).

In conclusion, the present study has shown that submaximal clenching the jaw did not significantly affect balance recovery of healthy young adults in terms of dynamic postural stability and lower extremity joint kinematics after forward loss of balance. This is probably due to the different control strategies associated with static postural control and balance recovery after simulated forward falls, which is manifested by the absence of significant correlations. One must, therefore, question whether (i) the ergogenic effects of jaw clenching are limited only to static postural control, or (ii) the contradictory results might have been evoked by the methodological approach, the bite forces itself, or the study sample. Conclusive evidence is lacking, however.

On the other hand, one might argue that reductions in CoP displacement – as they have been observed in response to jaw clenching (Hellmann et al., 2011c; Ringhof et al., 2015c) and centric jaw relation (Gangloff et al., 2000; Bracco et al., 2004; Sakaguchi et al., 2007) – could degrade postural control performance. According to Haddad et al. (2013), postural variability in terms of increased CoP displacements is considered to aid in the exploration of the environment and to allow to experience the boundaries of stability (van Emmerik & van Wegen, 2002). However, this explanatory behavior might be valid only as long as postural sway does not cause a loss of balance, and rather may facilitate postural control during postural perturbation, when increased CoP displacement may make it easier to regain balance. For static postural control, this assumption, therefore, should be regarded critically; particularly, as this explanatory behavior increases the risk of losing balance by decreasing the margin of stability.

Future studies should contrast the effects of submaximal biting in different populations, under conduction of random perturbations, and as compared to both open mouth and habitual control conditions.

7 Golf Performance during Voluntary Jaw Clenching

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7.1 Abstract

Human motor control is based on complex sensorimotor processes. Recent research has shown that neuromuscular activity of the craniomandibular system (CMS) might affect human motor control. In particular, improvements in postural stability and muscle strength have been observed as a result of voluntary jaw clenching. Potential benefits of jaw aligning appliances on muscle strength and golf performance have also been described. These reports are highly contradictory, however, and the oral motor task performed is often unclear. The purpose of our study was, therefore, to investigate the effect of submaximal biting on golf performance via shot precision and shot length over three different distances. Participants were 14 male professional golfers – seven with sleep bruxism and seven without – randomly performing golf shots over 60 m, 160 m, or driving distance while either biting on an oral splint or biting on their teeth; habitual jaw position served as the control condition. Statistical analysis revealed that oral motor activity did not systematically affect golf performance in respect of shot precision or shot length for 60 m, 160 m, or driving distance. These findings were reinforced by impact variables such as club head speed and ball speed, which were, also, not indicative of significant effects. The results thus showed that the strength improvements and stabilizing effects described previously are, apparently, not transferable to such coordination-demanding sports as golf. This could be due to the divergent motor demands associated with postural control and muscle strength on the one hand and the complex coordination of a golf swing on the other. Interestingly, subjects without sleep bruxism performed significantly better at the short distance (60 m) than those with bruxism. Because of the multifactorial etiology of parafunctional CMS activity, conclusions about the need for dental treatment to improve sports performance are, however, completely unwarranted.

7.2 Introduction

Human motor control is based on the complex interaction of dynamic processes comprising, e.g., diverse sensory systems, intermuscular and intramuscular synergy, and, thereby, coordination of several joints with several degrees of freedom (Horak, 2006). In recent decades, numerous research on human motor control have suggested the potential effect of dental occlusion and muscle activity of the craniomandibular system (CMS). These suggestions arose from animal studies which revealed neuroanatomical connection of the trigeminal nerve to several structures associated with postural control (Buisseret-Delmas et al., 1999). Trigeminal projections to all levels of the spinal cord have also been found (Ruggiero et al., 1981; Devoize et al., 2010). Subsequent investigation of the effects of oral motor activity among humans revealed modulation of reflexes (Miyahara et al., 1996) and facilitation of motor system excitability (Boroojerdi et al., 2000) as a result of jaw clenching. Takada et al. (2000) concluded that these effects might contribute to increased stability in stance rather than to smoothness of movements.

Several studies have confirmed the neuromuscular effect of oral motor activity and different jaw relations on postural control during upright unperturbed stance (Bracco et al., 2004; Sforza et al., 2006; Sakaguchi et al., 2007; Tardieu et al., 2009). More precisely, decay of center of pressure displacements induced by submaximal biting has been revealed by posturographic analysis (Hellmann et al., 2011c; Ringhof et al., 2015c). Similar to the stabilizing effects, significant increases in force production and rate of force development when clenching the jaw have been described (Forgione et al., 1991; Hiroshi, 2003; Ebben et al., 2008). Ebben et al. (2008) suggested that the effects were caused by concurrent activation potentiation which, in turn, enhanced the neural drive to the distal muscle groups.

Increasing attention has also been focused on athletic performance and the potential benefits of oral appliances, in general, and mandibular orthopedic repositioning appliances (MORA), in particular. These devices were used either to voluntarily interfere with dental occlusion, and thus to disturb optimum systemic function, or to properly align the mandible relative to the maxilla, to achieve an effective physiologic state. In an experiment with highly proficient marksmen, performance was found to be significantly better when the mandible was in symmetric centric relation, as compared with intercuspal or lateral occlusion, an effect primarily attributed to postural stabilization (Gangloff et al., 2000). Ergogenic effects resulting from use of jaw-aligning appliances have also been observed in measurement of muscle strength (Kaufman & Kaufman, 1985; Forgione et al., 1991; Forgione et al., 1992; Gelb et al., 1996; Arent et al., 2010; Dunn-Lewis et al., 2012). Significant increases in muscle strength of the upper and lower extremities and improvements in vertical jump height have been observed for athletes wearing oral devices. Some of this work has been criticized, however, primarily because of weak experimental design and lack of control conditions (Jakush, 1982; McArdle et al., 1984). Other studies, in turn, have failed to observe alteration of muscle strength as a result of the use of oral appliances (Cetin et al., 2009; Allen et al., 2014; Golem & Arent, 2015), thus questioning the aforementioned ergogenic effects. These results are further reinforced by studies using double-blind tests which claimed that performance enhancements by use of MORAs and other stabilizing splints are simply a result of placebo effects (Burkett & Bernstein, 1983; Allen et al., 1984; McArdle et al., 1984; Chiodo & Rosenstein, 1986).

Despite this controversy, many authors still argue in favor of performance benefits, and have examined further the effects of oral appliances in diverse sports. In this context, recent studies investigated the performance of golf professionals while using stabilizing splints. Whereas Egret et al. (2002) observed significant reductions in ball speed variability but no changes in average ball speed and kinematic pattern of the golf swing, Kwon et al. (2010) and Pae et al. (2013) observed significant improvements in driving distance and club head speed when the oral appliances were being used. Because accurate hitting of the ball and transfer of as much momentum as possible to the ball are important aspects of improving one’s driving distance (Hume et al., 2005), it was suggested that the improvements were induced by increased focus of attention at the moment of impact and/or increased muscle strength in the upper and lower extremities. The latest study by Pae et al. (2013) demonstrated, however, that use of an adjusted oral splint may aid optimization of driving distance and club head speed but not initial ball speed and putting accuracy. Improved driving distance hence seemed more likely to be the result of enhanced muscle strength rather than increased focus.

Some weak points of the abovementioned studies – which also might have contributed to the controversy – are the lack of information concerning the generated bite forces and the mandibular positions during the experiments. In particular, when assessing the impact of jaw-aligning appliances on strength and golf performance, the actual oral motor activity while wearing the splints mostly remained unknown (Allen et al., 2014). Other studies used simple over-the-counter appliances, which in turn altered jaw relation to an undefined position or irritated the subjects because of their uncomfortable fit (Golem & Arent, 2015). In the case that custom-made splints were applied, terms like centric relation were used to describe the experimental jaw position (Gangloff et al., 2000). But, since there is no international consensus about the definition of a physiological centric jaw relation (Keshvad & Winstanley, 2000), the common used phrase of symmetric positioning of the mandible in centric relation is not meaningful, and the jaw positions as experimental conditions are thus not comparable.

Because of the consistent effects of jaw clenching on motor system excitability, therefore, two important questions arise: first, are the contradictory reports merely a consequence of diverse, potentially affecting task instructions – i.e. to perform normally or to bite on the respective splint – and, second, does biting on oral devices lead to different results from biting on one’s teeth? This is of particular interest, because investigation of the effect of jaw clenching itself has not yet been reported for golf or similar coordination-demanding sports.

The purpose of this study was, therefore, to investigate the effect of controlled oral motor activity, in the form of submaximal biting tasks, on the athletic performance of professional golf players. Golf performance was evaluated for short (60 m), medium (160 m), and driving distances, and compared for three biting tasks – submaximal biting on one’s teeth, submaximal biting on an oral splint, and habitual jaw position, which served as the control condition. It was hypothesized that submaximal biting increases driving distance in general and, more specifically, biting on an oral splint improves driving distance to a greater extent than biting on one’s teeth. For 60 m and 160 m, however, the authors supposed that the shot precision is not affected by oral motor tasks.

7.3 Materials and methods

7.3.1 Subjects

Fourteen professional golfers participated in this study. Subjects were exclusively male, all playing in the first or second German Golf League. The participants were naïve to the experimental procedure and had no known muscular or neurological diseases that could have affected their ability to perform the experiments. All the subjects had normal vision and presented with full dentition (except for third molars) in neutral occlusion (Angle class I). Moreover, they all had no symptoms of TMD (Reissmann et al., 2009), whereas seven reported sleep bruxism.

The study was reviewed and approved by the Ethics Committee of the German Sports University, Cologne (no. 38/12). All subjects gave their written informed consent to the experiments, which were conducted in accordance with the Declaration of Helsinki.

7.3.2 Experimental design

The effects of oral motor tasks on golf performance were assessed by use of a crossover design in which three different shot distances and three oral motor tasks were compared. All subjects completed five trials per shot distance per oral motor task, i.e. 45 golf shots in total. To avoid any effects of learning or fatigue, shot distances and oral motor tasks were randomly assigned for each subject. Before testing, each subject was given standardized verbal instructions about the experimental procedure. During a warm-up session subjects were familiarized with the golf shots and oral motor tasks, first separately and then in combination. This was to ensure the subjects were capable of constantly maintaining the respective jaw motor task at the desired activity level. Finally, maximum voluntary contraction (MVC) of the masseter was recorded.

Golf shots

Golf shots were performed over three distances – short (60 m), medium (160 m), and driving distance (Drive). The required shot directions and lengths were displayed to the participants in the form of pylons which were positioned at the respective locations. Based on their individual capabilities, subjects chose a sand or lob wedge for 60 m, a ‘mid iron’ from five to seven for 160 m, and a driver for Drive, respectively. The subjects, however, were not allowed to change the clubs between shots over the same distance.

To quantify golf performance for all three shot distances, a radar-based system (TrackMan Pro; TrackMan A/S, Vedbæk, Denmark) was used. Trackman Pro is a commercially available product widely used by professional golfers and coaches. By tracking the club head and measuring the trajectory of the golf ball, TrackMan Pro delivers data on impact, ball flight characteristics as well as on shot distance and direction. With accuracy of 0.33 m at 100 m, this system thus provides appropriate and sufficiently precise information on golf performance.

Oral motor tasks

Before and during the golf swing, subjects were asked to bite either on their teeth (B_T) or on an oral splint (B_S); hitting with habitual jaw position (HJP) served as the control condition. HJP in this context could, for instance, involve interocclusal spacing between mandible and maxilla or just biting activity as well. B_T and B_S were both performed at submaximal masseter activity of 25% MVC. To control for this coordinative task, visual biofeedback of the electromyographic activity (EMG) of the masseter muscle was presented to the participants. The raw EMG signals were rectified, smoothed (100 points moving median), and scaled to the previously recorded MVC data in real time. The feedback monitor was directly positioned behind the golf ball, enabling the subjects to shift their gaze from the monitor to the ball without much head movement.

EMG data for the masseter were recorded by use of bipolar surface electrodes (Ag/AgCl) and Noraxon telemetric equipment (TeleMyo 2400 G2; Noraxon, Scottsdale, AZ, USA). The EMG signals were collected with a sampling frequency of 1,000 Hz and amplified by a factor of 500. The electrodes, which had a diameter of 14 mm and a center-to-center distance of 20 mm, were applied bilaterally to the belly of the masseter, in line with the direction of the muscle fibers. The ground electrode was positioned on the seventh cervical vertebra. Before application, the skin over the participants’ muscles was properly prepared by shaving, abrasion, and cleaning with alcohol.

During B_S, the subjects were asked to bite submaximally on an intra-oral splint. The splint used in the present study (Aqualizer, medium volume; Dentrade International, Cologne, Germany) was a commercially available device based on a fluid self-adjusting system that distributes bite force evenly across the bite. The splint thus enables a physiologic autobalanced static equilibrium of the CMS (Hellmann et al., 2011b) with an interocclusal vertical height of 1–3 mm.

All oral motor tasks had to be performed for at least three seconds before the golf shots. When this was achieved, the subjects were instructed to focus their attention on the golf shot, but to maintain the required activity level as best they could during the entire golf swing, as practiced during the warm-up session.

7.3.3 Data analysis

Golf performance

To assess golf performance, diverse length-specific performance variables were included in the evaluation. With regard to the 60-m and 160-m shots, when golfers are seeking best approach to the pin, precision is the key factor determining golf performance. Hence, the resulting distance to pin ($\text{Pin}_{\text{total}}$) was chosen as the dependent variable of interest. To give more detailed information on shot precision, both lateral (Pin_{side}) and longitudinal ($\text{Pin}_{\text{length}}$) distance to pin were also evaluated for each shot. The purpose of the Drive is, however, to transfer as much momentum as possible to the ball and thus achieve the desired shot length. Consequently, when investigating Drive performance, the shot length achieved (Carry) and Pin_{side} are of primary interest.

In addition to the abovementioned performance variables, club and ball data were evaluated for all the shot distances tested. Impact variables included club head speed immediately before impact ($\text{Speed}_{\text{club}}$) and ball speed immediately after impact ($\text{Speed}_{\text{ball}}$). Moreover, the smash factor (Smash), represented as the ratio of $\text{Speed}_{\text{ball}}$ to $\text{Speed}_{\text{club}}$, and the launch angle (Angle), indicating the angle at which the ball takes off relative to the ground, were analyzed.

Masseter EMG

The masseter EMG signals not only served as biofeedback for the subjects, but were also assessed to investigate masseter activity before and during the golf swing. For this purpose, the raw signals were initially rectified, smoothed (100 ms), and scaled to the MVC data. These data were then used to compare intended (25% MVC) and actual masseter activity by calculating the average EMG values for the time the subjects remained in the address position (MA_{pre}). To moreover contrast masseter activity during the golf swing, the mean (MA_{swing}) and maximum EMG amplitudes (MA_{max}) from 900 ms before until 350 ms after impact with the ball were analyzed for the different test conditions. This time period corresponds to the mean duration of the swing of professional golfers, starting with initiation of the backswing and ending with the so-called follow-through (Egret et al., 2002; Meister et al., 2011).

7.3.4 Statistics

Statistical analysis was performed by use of IBM SPSS Statistics 21.0 (IBM Corporation, Armonk, NY, USA). First, Kolmogorov-Smirnov tests were applied to confirm the normality of data distribution. Mauchly's tests of sphericity were then conducted to determine whether the assumption of sphericity was violated. When this did occur, Greenhouse-Geisser estimates were used to correct for any violations.

To test for differences between subject characteristics of the bruxism and non-bruxism groups independent *t*-tests were conducted. The effects of oral motor tasks [B_T, B_S, HJP] on golf performance were investigated by one-way repeated measures ANOVA, performed separately for each shot distance [60 m, 160 m, Drive]. In a second step, two-way repeated measures ANOVA was conducted to test for statistical differences between subjects with and without sleep bruxism, and to reveal possible interaction effects with the oral motor tasks.

For EMG analysis, one-sample *t*-tests were used to contrast intended (25% MVC) and actual masseter activity before the golf swing (MA_{pre}) for both submaximal biting tasks [B_T, B_S]. Two-way repeated measures ANOVAs, performed separately for each shot distance, were applied to detect statistical differences between MA_{pre} for oral motor tasks and for subjects with and without sleep bruxism. Finally, mean (MA_{swing}) and maximum (MA_{max}) masseter activity during the golf swing were compared by three-way repeated measures ANOVAs, in which sleep bruxism [Yes, No] acted as between-subject factor, and oral motor task [B_T, B_S, HJP] and shot distance [60 m, 160 m, Drive] served as within-subject factors. Bonferroni corrections were used to adjust for multiple comparisons.

Table 7.1 Subject characteristics.

Group	Subjects [n]	Age [years]	Height [m]	Mass [kg]	BMI [kg/m²]	HCP
Total	14	21.39 ± 3.93	1.83 ± 0.04	74.43 ± 6.57	22.08 ± 1.37	0.1 ± 1.7
Bruxism	7	24.09 ± 5.18	1.85 ± 0.02	78.86 ± 7.19	22.93 ± 1.64	-1.5 ± 1.9
No bruxism	7	18.69 ± 0.94	1.81 ± 0.04	70.00 ± 5.14	21.23 ± 0.91	1.4 ± 1.0

All data are presented as mean ± $CI_{95\%}$.
BMI = body mass index; HCP = handicap.

All results are reported as mean values with 95% confidence intervals. Partial eta squared (η_p^2) is indicated to give information about effect sizes. For small effects $\eta_p^2 = 0.01$, for medium effects $\eta_p^2 = 0.06$, and for large effects $\eta_p^2 = 0.14$ (Cohen, 1988; Richardson, 2011). For all statistical tests, the level of significance was set a priori to $p = 0.05$.

7.4 Results

The subject characteristics are listed in Table 7.1. Independent *t*-tests indicated no significant differences between bruxism and non-bruxism groups for the variables under investigation.

Golf performance

Figure 7.1 shows the length-specific performance variables as functions of the factors under investigation. Statistical analysis revealed that oral motor tasks did not statistically affect golf performance with respect to Pin_{total} for either the short (60 m) or medium distance (160 m). Apart from this, Pin_{side} was not significantly altered by the submaximal biting task, either for 60 m or 160 m. These non-significant main effects of oral motor task were, moreover, found for Pin_{length} at 60 m. In contrast, oral motor tasks had a statistically significant effect on Pin_{length} at 160 m [$p = 0.043$, $\eta_p^2 = 0.22$]. Bonferroni adjustments indicated that, compared with the golf shots under B_S and HJP, the distance from the pin was significantly reduced during B_T [$p = 0.040$ and $p = 0.043$, respectively]. The submaximal biting tasks had no statistically significant effects on Carry at driving distance, however. There were, furthermore, no main effects on Pin_{side} at this distance.

When subjects with and without sleep bruxism were compared, two-way repeated measures ANOVA revealed significant differences for Pin$_{total}$ at 60 m [$p = 0.035$, $\eta_p^2 = 0.32$], indicative of better performance for subjects without bruxism, whereas for 160 m and Drive no main effects of sleep bruxism were observed. There were, in addition, no

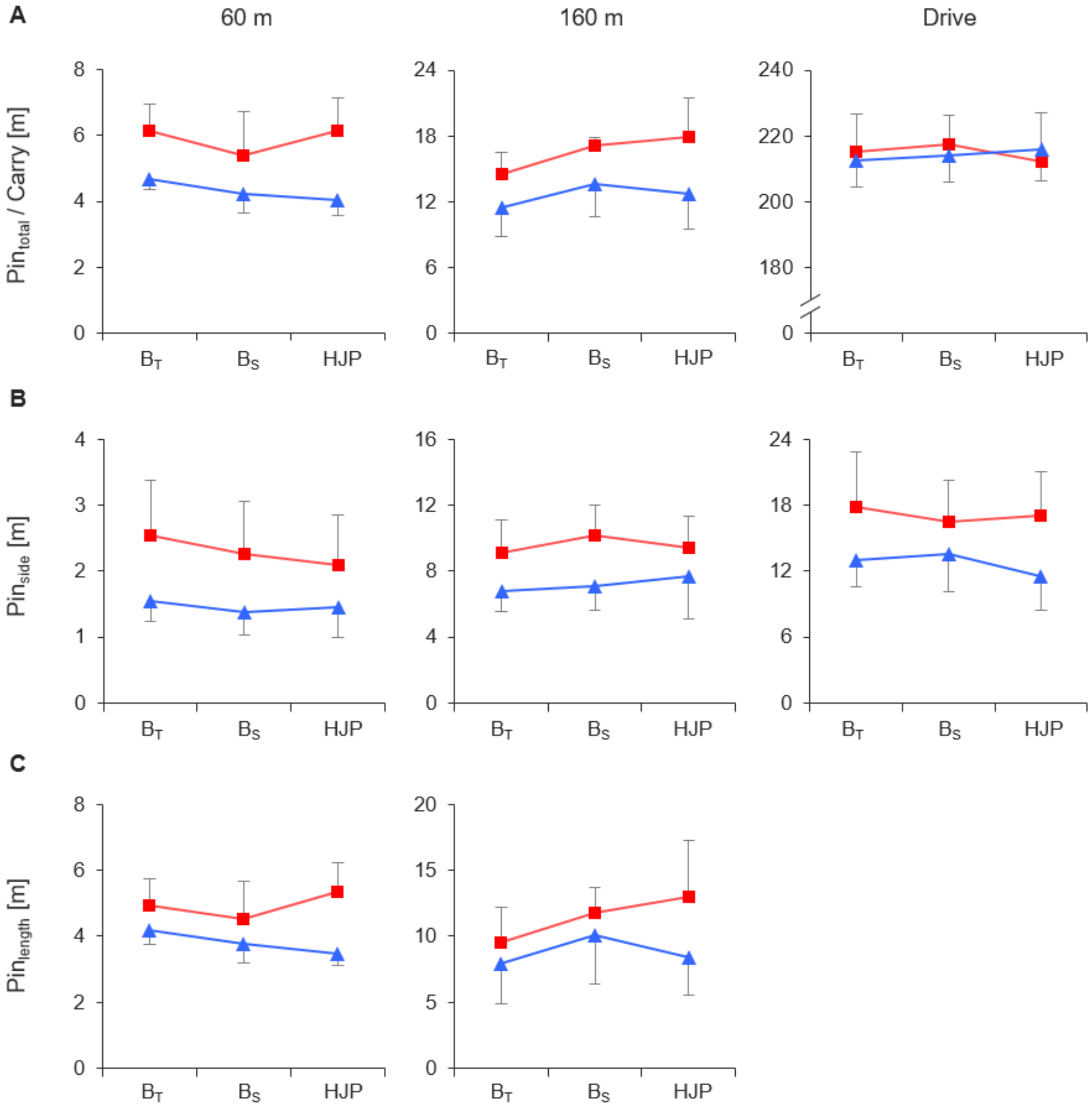

Figure 7.1 Performance variables for 60 m, 160 m, and Drive as functions of sleep bruxism (bruxism = red; no bruxism = blue) and oral motor tasks (B$_T$ = biting on teeth; B$_S$ = biting on splint; HJP = habitual jaw position). **A**, total distance to pin (Pin$_{total}$) at 60 m and 160 m, and shot length (Carry) at Drive; **B**, lateral distance to pin (Pin$_{side}$); **C**, longitudinal distance to pin (Pin$_{length}$). All data are presented as mean ± CI$_{95\%}$.

oral motor task × bruxism interaction effects for any performance variable. Detailed information on intra-individual and inter-individual performance as functions of the oral motor tasks – available in Appendix S2 – shows that, particularly for the 60 m shot distance, some athletes (subjects 1, 4, 8, 9, 11, 13, and 14) benefited markedly from biting on the oral splint.

With regard to the impact variables (Table 7.2), oral motor tasks solely influenced $\text{Speed}_{\text{club}}$ [$p = 0.012$, $\eta_p^2 = 0.31$] at 60 m. Bonferroni adjustments for multiple comparisons revealed significant differences between B_S and HJP [$p = 0.014$]. For the 60 m shot distance, impact variables were also affected by sleep bruxism. Significant main effects were found for $\text{Speed}_{\text{club}}$ [$p = 0.032$, $\eta_p^2 = 0.33$], $\text{Speed}_{\text{ball}}$ [$p = 0.003$, $\eta_p^2 = 0.53$], and Angle [$p = 0.049$, $\eta_p^2 = 0.29$], whereas significantly higher speeds and larger angles were observed for subjects with bruxism. With regard to the 160 m shots, statistical analysis revealed

Table 7.2 Impact variables for each shot distance as functions of oral motor tasks and sleep bruxism.

Variable	Bruxism			No bruxism		
	B_T	B_S	HJP	B_T	B_S	HJP
$\text{Speed}_{\text{club}}$ [m/s]						
60 m	28.89 ± 1.34	29.12 ± 1.40	28.54 ± 1.27	25.70 ± 1.38	26.09 ± 1.35	25.44 ± 1.60
160 m	41.46 ± 1.61	41.46 ± 1.54	41.55 ± 1.52	39.79 ± 1.04	39.78 ± 1.11	39.67 ± 1.02
Drive	48.23 ± 1.69	48.27 ± 1.64	48.15 ± 1.81	46.58 ± 1.51	46.67 ± 1.61	46.60 ± 1.58
$\text{Speed}_{\text{ball}}$ [m/s]						
60 m	29.15 ± 0.53	29.14 ± 0.51	29.07 ± 0.38	27.97 ± 0.46	27.98 ± 0.33	27.57 ± 0.50
160 m	54.82 ± 1.84	54.34 ± 1.20	53.98 ± 2.10	54.05 ± 1.09	54.05 ± 1.40	54.03 ± 1.03
Drive	68.45 ± 2.53	68.71 ± 2.48	68.09 ± 3.13	67.19 ± 2.00	67.07 ± 1.92	66.86 ± 2.21
Smash [%]						
60 m	1.02 ± 0.05	1.01 ± 0.04	1.02 ± 0.04	1.10 ± 0.06	1.08 ± 0.06	1.10 ± 0.07
160 m	1.32 ± 0.02	1.31 ± 0.03	1.30 ± 0.02	1.36 ± 0.01	1.36 ± 0.01	1.36 ± 0.01
Drive	1.42 ± 0.03	1.42 ± 0.02	1.41 ± 0.03	1.44 ± 0.02	1.44 ± 0.02	1.44 ± 0.02
Angle [°]						
60 m	39.32 ± 1.83	39.59 ± 1.31	39.48 ± 1.36	36.34 ± 2.06	36.31 ± 2.18	36.11 ± 1.34
160 m	15.51 ± 1.14	14.96 ± 0.99	15.28 ± 1.00	13.57 ± 1.11	13.23 ± 1.00	13.67 ± 1.02
Drive	12.70 ± 1.34	12.49 ± 1.33	13.22 ± 1.64	12.09 ± 0.46	12.62 ± 0.63	12.87 ± 0.42

All data are presented as mean ± $\text{CI}_{95\%}$.
B_T = biting on teeth; B_S = biting on splint; HJP = habitual jaw position; $\text{Speed}_{\text{club}}$ = club head speed immediately before impact; $\text{Speed}_{\text{ball}}$ = ball speed immediately after impact of the club; Smash = smash factor ($\text{Speed}_{\text{ball}}/\text{Speed}_{\text{club}}$); Angle = angle at which the ball takes off, relative to the ground.

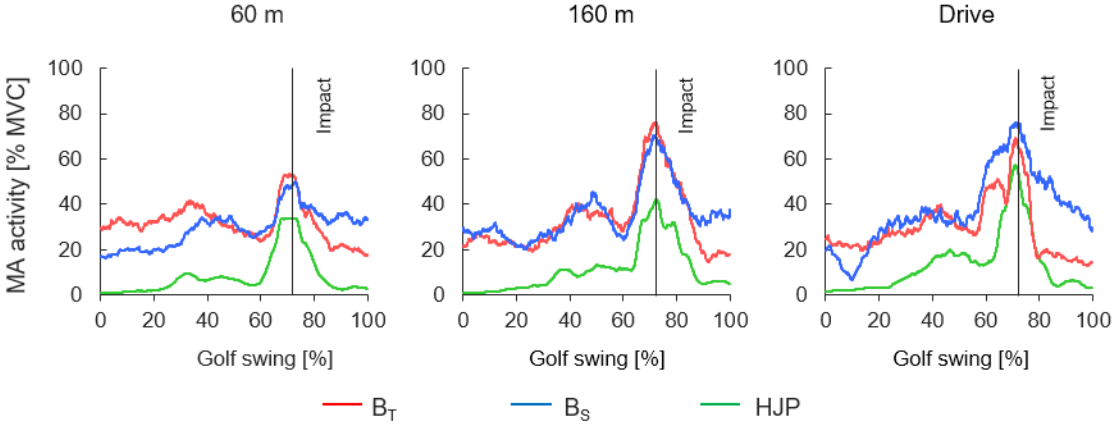

Figure 7.2 Typical time courses of the masseter activity from initiation of the backswing (0%) until follow-through (100%) for 60 m, 160 m, and Drive as functions of oral motor tasks.
MA = masseter; MVC = maximum voluntary contraction; B_T = biting on teeth; B_S = biting on splint HJP = habitual jaw position.

significant differences exclusively for Smash [$p = 0.005$, $\eta_p^2 = 0.50$], in terms of higher factors for subjects without bruxism. Besides, there were no interactions between oral motor tasks and sleep bruxism for any impact variable for all shot lengths, and no statistical differences related to Drive.

Masseter EMG

All results relating to masseter activity before (MA_{pre}) and during the golf swing (MA_{swing}, MA_{max}) are listed in Table 7.3. Typical time courses of the masseter activity during the golf swing can be obtained from Figure 7.2.

With regard to MA_{pre}, one-sampled *t*-tests showed that for neither B_T nor B_S did the effectively realized masseter activity deviate significantly from the intended activity of 25% MVC. This was true for all shot distances and both subpopulations, i.e. subjects with and without sleep bruxism. Two-way repeated measures ANOVA revealed, moreover, no statistical difference between MA_{pre} for B_S and B_T, but significant less masseter activity during HJP than during B_S and B_T for all shot distances [each $p < 0.001$].

For MA_{swing}, three-way repeated measures ANOVA indicated main effects of oral motor task [$p < 0.001$, $\eta_p^2 = 0.74$] and shot distance [$p < 0.001$, $\eta_p^2 = 0.66$]. MA_{swing} increased significantly with shot distance [60 m vs. 160 m: $p = 0.007$; 60 m vs. Drive: p

= 0.001; 160 m vs. Drive: $p = 0.013$], and was significantly higher for B_T and B_S than for HJP [$p = 0.001$ and $p < 0.001$, respectively]. There were, in contrast, no statistically significant differences between B_T and B_S, and no bruxism or interaction effects.

Similar results were obtained for MA_{max}. Statistical analysis revealed main effects of oral motor task [$p < 0.001$, $\eta_p^2 = 0.60$] and shot distance [$p < 0.001$, $\eta_p^2 = 0.60$]. Bonferroni adjustments for multiple comparisons indicated that MA_{max} was significantly lower for HJP and 60 m than for the submaximal oral motor tasks [B_T vs. HJP: $p = 0.002$; B_S vs. HJP: $p = 0.001$] and the longer shot distances [60 m vs. 160 m: $p = 0.005$; 60 m vs. Drive: $p = 0.002$], respectively. In addition, a significant oral motor task × bruxism interaction effect was observed [$p = 0.044$, $\eta_p^2 = 0.25$]. Whereas for subjects without sleep bruxism a clearly different MA_{max} between HJP and both submaximal biting tasks was observed, the EMG amplitudes for subjects with bruxism were very high during HJP and only slightly lower than those during B_T and B_S.

Table 7.3 Masseter activity before and during the golf swing for each shot distance as functions of oral motor tasks and sleep bruxism.

Variable	Bruxism			No bruxism		
	B_T	B_S	HJP	B_T	B_S	HJP
MA_{pre} [%]						
60 m	23.84 ± 1.79	23.99 ± 1.71	2.14 ± 0.74	24.81 ± 3.44	23.65 ± 3.72	1.98 ± 0.60
160 m	23.41 ± 1.26	24.37 ± 2.29	1.98 ± 0.74	23.42 ± 2.85	22.83 ± 3.80	2.77 ± 1.50
Drive	25.46 ± 2.29	25.11 ± 2.63	1.77 ± 0.83	24.61 ± 3.46	22.51 ± 3.43	1.84 ± 0.64
MA_{swing} [%]						
60 m	17.10 ± 7.68	21.68 ± 5.65	10.30 ± 8.23	21.52 ± 6.35	19.63 ± 5.55	9.08 ± 6.51
160 m	23.85 ± 10.68	26.85 ± 8.58	17.35 ± 11.55	24.34 ± 7.43	28.26 ± 7.12	15.32 ± 10.37
Drive	26.33 ± 9.80	33.32 ± 10.87	18.45 ± 12.08	30.80 ± 7.75	33.03 ± 8.63	14.29 ± 7.17
MA_{max} [%]						
60 m	43.11 ± 25.88	49.59 ± 19.23	38.25 ± 30.95	57.37 ± 32.83	50.95 ± 27.64	36.07 ± 29.58
160 m	71.56 ± 39.91	72.41 ± 35.17	69.34 ± 41.64	71.36 ± 32.09	77.40 ± 37.10	56.09 ± 37.15
Drive	79.09 ± 39.19	87.09 ± 42.11	67.30 ± 39.40	82.15 ± 33.23	80.36 ± 33.91	48.33 ± 20.91

All data are presented as mean ± $CI_{95\%}$.
B_T = biting on teeth; B_S = biting on splint; HJP = habitual jaw position; MA_{pre} = mean masseter activity before golf swing; MA_{swing} = mean masseter activity during golf swing; MA_{max} = maximum masseter activity during golf swing.

7.5 Discussion

The purpose of this study was to investigate the effects of oral motor activity on the athletic performance of professional golfers. The authors hypothesized that submaximal biting would significantly increase drive distance whereas shot precision at 60 m and 160 m would be unaffected by these jaw motor tasks.

Before discussing the obtained results, first it must be mentioned that the requested activity level before the shot (25% MVC) was achieved by the subjects for both force-controlled biting conditions, with no statistical differences between B_S and B_T, but significantly higher MA_{pre} than during HJP. This forms the basis for the further discussion, enabling comparability of the results and conclusive statements.

With regard to the primary length-specific performance variables (Pin_{total} at 60 m and 160 m, and Carry at Drive), statistical analysis revealed no significant differences between oral motor activity. Even when golf performance is considered in more detail, neither lateral (Pin_{side}) nor longitudinal (Pin_{length}) distance to pin were statistically affected by submaximal biting. The only exception was for Pin_{length} at 160 m, which was significantly improved for B_T compared with B_S and HJP. The outcomes were similar for the impact variables ($Speed_{club}$, $Speed_{ball}$, Smash, Angle); again only $Speed_{club}$ at 60 m changed as a result of the oral motor tasks, with the velocity of the club head during B_S being significantly higher than during HJP. These results thus showed that, under the study conditions chosen, biting at a submaximal level did not systematically improve golf performance with regard to shot precision and shot length over three different shot distances; this conclusion is reinforced by the absence of statistically significant differences for the impact variables. In this context, it should also be noted that biting on the splint used in our study did not affect golf performance differently from biting on one’s teeth.

To the best of the authors’ knowledge, this study was the first to examine the effect of submaximal biting on golf performance. The results cannot, therefore, be compared with those from previous studies. For this reason, the authors focus on discussion of the general effect of the CMS on human movement in an attempt to provide possible explanations, without any claim to be comprehensive.

As already indicated above, several reports have described potential performance benefits, particularly improvements in strength (Kaufman & Kaufman, 1985; Forgione et al., 1991; Gelb et al., 1996; Dunn-Lewis et al., 2012) and driving distance (Kwon et al., 2010; Pae et al., 2013), induced by the use of jaw-aligning appliances. Taking into account that driving distance is very dependent on club head speed, which is, in turn, closely related to muscle strength of the upper and lower extremities (Hellström, 2009), it has been hypothesized that increases in driving distance resulted from improvement of muscle strength. Presumably, this is a result of optimum systemic function and reduced stress on the CMS, which is assumed to be important for achieving maximum athletic potential (Gabaree, 1981; Pae et al., 2013).

Ergogenic effects on muscle strength and power have also been described for jaw clenching tasks. When the jaw was clenched, Hiroshi (2003) and Ebben et al. (2008) observed significant increases in peak force and rate of force development during grip strength assessments and countermovement jumps, respectively. The latter authors suggested that these improvements were provoked by concurrent activation potentiation, which increased the neural drive to the skeletal muscles, thus, gaining the athlete an ergogenic advantage during strength-related motor tasks (Ebben et al., 2008). In this study, however, submaximal biting tasks were not shown to significantly improve the participants' driving distance or club head speed. There might be different reasons for this.

First, the facilitating (Miyahara et al., 1996; Boroojerdi et al., 2000) and stabilizing (Gangloff et al., 2000; Hellmann et al., 2011c; Ringhof et al., 2015c) effects of voluntary jaw clenching are not transferable to coordination-demanding full-body motion, like golf swings. This could be due to the divergent motor demands associated with postural control and shooting on the one hand, and golf swing on the other. Whereas the former are primarily based on feedback mechanisms and fine motor control (Horak, 2006), the latter requires whole-body coordination mainly associated with feedforward control – especially in experts. Modulation of somatosensory input, particularly for the neck muscles (Abrahams, 1977), and facilitation of ankle extensor and flexor muscles concomitant with attenuated reciprocal Ia inhibition from the pretibial muscles to the soleus muscle (Takada et al., 2000) by means of trigeminal connections and projections (Ruggiero et al., 1981; Devoize et al., 2010) might, thus, be not an issue.

Second, golf swings are not just simple strength-related, single or double joint movements. Golfers usually try to increase the torque applied to the club by summation of speed on the basis of successive actions of the hip, trunk, and shoulders, followed by motion of the arms, wrists, and hands (Burden et al., 1998; Egret et al., 2002). One must, therefore, question to what extent golf swings actually depend on muscle strength of the upper and lower extremities, and whether the observed performance benefits resulting from use of jaw-aligning appliances (Egret et al., 2002; Kwon et al., 2010; Pae et al., 2013) are effectively due to strength improvements. This investigation cannot resolve this question, however.

The last, and probably most conclusive, factor to be considered is that the above-mentioned research on the impact of jaw clenching on muscular force development used an open mouth, non-clenching condition as control (Hiroshi, 2003; Ebben et al., 2008). Specifically, the participants in the investigations of Hiroshi (2003) and Ebben et al. (2008) were instructed to clench their jaw to the maximum extent or to keep their mouth open while performing the grip strength tests and countermovement jumps, respectively. In the present study, however, submaximal biting was compared with habitual jaw position, in which subjects were asked to perform the golf shots as normally as possible. In this context, it should be mentioned that, on the one hand, even professional golfers could not easily perform golf swings with their mouth open (Egret et al., 2002); on the other hand it should be noted that the subjects in our study, even under habitual conditions, clenched their teeth while performing the golf shots. Interestingly, both mean and maximum masseter activity during the golf swing increased significantly with requested shot distance. Clenching the jaw, hence, might be a common physiological strategy used to improve the neural drive to distal body segments and by this means enhance performance. This, in turn, would indicate that Hiroshi (2003) and Ebben et al. (2008) actually did not observe muscle strength improvements when the jaw was clenched, but rather a decrease in force development during the non-clenching condition.

Although the effect of bruxism was not the focus of this study, it had significant impact on golf shots over the short distance. Descriptively, all performance variables turned out worse for the golfers with sleep bruxism, especially under HJP conditions. Statistically, however, only $\text{Pin}_{\text{total}}$ at 60 m was revealed to be significantly worse as compared to the healthy subjects, possibly as a result of greater club head speed and ball speed at impact. There is consensus about the multifactorial nature of the etiology of bruxism. In the past, morphological factors, for example occlusal discrepancies and the anatomy of the bony structures of the orofacial region, were believed to be the main causative factors of bruxism. Nowadays, however, these factors are believed to be of minor or no importance. It has been suggested that bruxism is part of a sleep arousal response modulated by a variety of neurotransmitters in the central nervous system. More specifically, disturbances in the central dopaminergic system have been linked to bruxism. Psychological factors, for example stress and personality, are also frequently mentioned in relation to bruxism, but research results are controversial (Lobbezoo & Naeije, 2000; Cuccia, 2008). Considering the multifactorial etiology of bruxism, further research is needed to elucidate the potential influence of bruxism on the performance of professional golfers. On the basis of our results it might be speculated that bruxism causes structural and functional changes (Ahlgren et al., 1969; Iida et al., 2014), which finally might impair motor performance during coordination-demanding tasks. The authors would like to point out, however, that on the basis of the present study and the literature available, conclusions on the need for dental treatment to improve sports performance are completely unwarranted.

In conclusion, this study has demonstrated that jaw motor activity, in terms of submaximal biting, did not systematically affect the performance of professional golfers; whereas no differences were observed for biting on an oral splint, biting on one’s teeth, and habitual jaw position. On the other hand, it can be stated that neither submaximal biting nor the oral appliance used in our investigation impeded the athletes’ golf performance significantly. Essentially, however, particularly in high-level sports, the athlete and potential intervention to improve performance should always be regarded individually. Notwithstanding this, it remains unclear whether the contradictory reports regarding muscle strength and golf assessment in combination with jaw clenching or jaw aligning appliances are not just the result of divergent methods and control conditions. Future studies should, thus, contrast the effects of oral motor activities as a result of both open mouth and habitual conditions.

8 General Discussion

The purpose of the present thesis was to investigate the effects of concurrent oral motor activities on human motor control and sports performance. Within this framework, this thesis focused on (i) the influence of jaw clenching on static postural stability, (ii) the influence of jaw clenching on dynamic postural stability, and (iii) the potential benefits of jaw clenching and the use of jaw-aligning splints on performance in professional golfers. To resolve the research questions involved, four studies encompassing the methods of static posturography, a simulated forward fall, and golf shot analyses were performed in conjunction with biomechanical motion analyses.

This chapter summarizes the main findings of the four studies described in Chapters 4 to 7 and discusses potential mechanisms of the observed phenomena. Further, some implications and recommendations for future research will be provided in this chapter.

8.1 Modulation of static postural control during concurrent clenching

Postural control – even in quiet stance – is a challenging task that is based on complex and permanent sensorimotor interaction. Sensory information from different receptors is transmitted via afferent pathways to the various systems of the CNS. Here, the input is processed in a task-specific manner, where-upon adequate motor commands with spinal or supraspinal origin are generated. Either in monosynaptic manner or along the corticospinal tract, these motor commands are transmitted to the distal muscle groups finally modulating posture.

Despite the general agreement on the complexity of this sensorimotor process and its high vulnerability to internally or externally induced modifications, the principles of sensory integration and neural control are still debated. Some research suggested that human postural control might be affected by the function and activity of the CMS (Cuccia

& Caradonna, 2009; Munhoz & Marques, 2009). Specifically, the impact of chewing and jaw clenching became a focus of recent investigations (e.g., Sforza et al., 2006; Hellmann et al., 2011c; Kushiro & Goto, 2011). However, due to inconsistent findings and methodological issues, the existence of a functional coupling between jaw motor activity and the postural control system is still controversially discussed; particularly as the mechanisms of this potential interaction yet remain to be clarified (Michelotti et al., 2011; Manfredini et al., 2012).

The studies depicted in Chapters 4 and 5 considered this issue and comprehensively investigated the effects of submaximal biting on static postural control using biomechanical motion analyses. By this means, the studies should enlighten this discrepancy and unravel the potential mechanisms of this interrelation, bridging the gap between prior investigations.

8.1.1 Concurrent jaw clenching decreases postural sway

The study reported in Chapter 4 focused on static postural control in bipedal narrow and unipedal stance and specifically examined the influence of concurrent submaximal jaw clenching compared to a non-clenching control condition. Jaw clenching was implemented in form of isometric jaw muscle contractions being visually controlled by use of real-time feedback. The study found that concurrently clenching the jaw had marked effects on postural control as indicated by significant alterations of postural sway. Specifically, both CoP sway area and CoP path lengths were significantly reduced during jaw clenching compared to the open-mouth, non-clenching control condition. These sway reductions were present across bipedal narrow stance as well as unipedal stance on dominant and non-dominant legs.

In view of the abovementioned findings, one could debate if postural sway is either decreased by the clenching task or rather increased by the non-clenching task. Taking further into account that Miyahara et al. (1996) found an increased soleus H-reflex for both clenching of the jaw and the fists, the question remained if these effects are specific to the jaw or whether clenching activities in general could influence postural sway. To overcome this lack of habitual and active controls, the follow-up study reported in Chapter 5 comparatively assessed postural sway during habitual standing, submaximally clenching the jaw and submaximally clenching the fists. All experimental conditions were performed on firm and foam surfaces to additionally investigate the impact of support surface conditions. It was found that – irrespective of the support surface – concurrent jaw and fist clenching both significantly decreased postural sway compared with the habitual control condition, however, with no differences between both concurrent clenching activities. By this means, the follow-up study emphasizes the impact of concurrent clenching activities on postural sway in general, and reinforces the virtue of jaw clenching compared to habitual and rest positions of the mandible. Concomitantly, this general modulation indicates that it is not the intra-oral splint that induced the sway reductions during jaw clenching, although a recent functional MRI study found higher cerebellar activity during jaw clenching on occlusal splints than on natural teeth (Ariji et al., 2016).

The findings obtained in Chapters 4 and 5 are consistent with some previous investigations (Hellmann et al., 2011c; Alghadir et al., 2015a). Those studies found similar improvements in postural stability when clenching the teeth, albeit methodologic deficiencies limit their significance. In general, the relation between postural control and jaw clenching remains elusive, particularly as the comparability between the few studies available is rarely given. Hellmann et al. (2011c) used a similar approach to that applied in the present studies. However, the measurement duration of three seconds was insufficient. Sforza et al. (2006) and Julià-Sánchez et al. (2015) compared the effect of clenching in different mandibular positions, but did not include habitual or non-clenching control conditions. Others examined the impact of mastication and reported postural sway to be significantly decreased while chewing gum when compared to open or resting jaw positions (Goto et al., 2011; Kushiro & Goto, 2011; Alghadir et al., 2015b). The most recent contribution to the overall controversy is associated with the work of Treffel et al. (2016). The authors failed to prove any influence of voluntary teeth clenching on static postural stability before and after three-day dry immersion and therefore cannot support our findings. Due to the insufficient description of the jaw motor task, the comparability is considerably aggravated, however.

The studies highlighted above predominately assessed the effects of CMS motor activity while upright unperturbed standing with feet hip-width apart. The experiments described in Chapters 4 and 5 were the first to investigate the effects of jaw clenching in more challenging static conditions, in particular, narrow and unstable support surfaces.

Having obtained significant improvements of postural stability in bipedal narrow and single-leg stance as well as on a foam surface, both experiments suggest postural gains from concurrent CMS activity to be independent of support conditions. Therewith, the present findings expand the stabilizing effects of jaw clenching to novel and challenging environments and further underpin the hypothesis of a functional coupling of the CMS and human posture. This linkage seems to come more strongly into effect in unstable conditions or when transiently perturbed by external forces (Tardieu et al., 2009; Julià-Sánchez et al., 2015).

Beyond that, the study in Chapter 4 was the first to assess the coordination and oscillations of upper body segments under these conditions. By employing 3D biomechanical motion analyses, it was shown that the reductions of CoP displacements were accompanied by decreased oscillations of cranial body segments as represented by pelvis, torso and head motions. Prior studies, which found jaw clenching to induce co-contractions of trunk muscles (Ehrlich et al., 1999) and an anterior shift of the CoP (Hellmann et al., 2011c), suggested that jaw muscle contractions might trigger an increased forward leaning of cranial body segments, presumably fostered by an enhancement of the tone of the anterior muscle chains. The results described in Chapter 4 refute this assumption. Although trunk and head oscillations were significantly reduced, jaw clenching did not influence the relative positions of the upper body segments with respect to the BoS. The hypothesized stiffening of anterior muscle chains therefore does not seem entirely convincing.

In essence, the aforementioned results reinforce the findings of some previous studies, highlighting and extending the stabilizing effect of concurrent clenching activities on static postural stability. However, whether this stabilization is reflecting an improved or impaired balance control is subject to extensive and still ongoing debates. In current literature, the prevailing opinion is that decreases in CoP displacements indicate an improved balance control. This opinion relates to epidemiologic studies showing strong associations between CoP displacements and the risk of falling (e.g., Maki et al., 1994; Era et al., 2006). Likewise, adaptations to balance training typically come along with decreased amount and variability of postural sway (for review, see Lesinski et al., 2015a; Lesinski et al., 2015b). Notwithstanding this indirect evidence, other researchers state that reductions in CoP displacement could represent a deterioration of postural control (van

Emmerik & van Wegen, 2002; Haddad et al., 2013). It is argued that postural variability – as indicated by increased CoP displacements – aids in the exploration of the environment and by this means allows to perceive the limits of stability. However, this exploratory behavior might only be valid as long as postural sway does not cause a loss of balance and rather could facilitate postural control during postural perturbation when increased CoP displacements simplify the detection and recovery of balance. For balance control under static condition, this assumption is regarded critically. In particular, the increased variability repeatedly decreases the margin of stability and therefore increases the risk of losing balance.

8.1.2 Concurrent jaw clenching does not affect the mechanisms of postural stability control

To bridge the gap between prior investigations and the various explanatory approaches, the study in Chapter 4 also aimed to enlighten the mechanisms potentially being responsible for the postural stabilization. Hereto, examinations of postural strategies and muscular co-contraction patterns by means of kinematic and EMG analyses were conducted.

The study showed that submaximal clenching the jaw did not systematically affect the postural strategy as indicated by the individual contributions of ankle and hip strategies to balance control. Furthermore, there were no detectable changes in the mean EMG of six postural muscles at the lower extremity. On the other hand, jaw clenching induced significantly reduced mean angular velocities at the lower extremity joints, which were accompanied by decreased variability of muscular co-contraction ratios of three muscle pairs. Although latter effects might indicate that jaw clenching indeed affected the mechanisms of postural control, it urgently needs to be emphasized that mean angular velocities were systematically decreased for all joints considered. Furthermore, the decreased variability of co-contraction ratios was not associated with decreased postural sway as revealed by Pearson's correlations. Therefore, these findings deny any changes in postural control mechanisms evoked by concurrently clenching the jaw.

Taken together, the kinematic and EMG analyses revealed that during jaw clenching (i) angular motions about the lower extremity joints were systematically decreased, (ii) balance was still primarily controlled by the ankle strategy with no changes in the main postural control strategies, (iii) mean activities of lower extremities muscles remained unaffected, and (iv) modulations of co-contractions patterns did not explain the enhancement of static stability. Therefore, the postural control system seems to use the same control mechanisms during jaw clenching and non-clenching conditions, but perhaps with an increased kinematic precision among the neuromuscular control patterns. Modulations within and between functional muscles groups are obviously not the reason for this.

8.1.3 Potential mechanisms of the observed phenomena

The study reported in Chapter 4 was the first to combine posturographic analyses with investigations of jaw clenching effects on muscular and joint coordination level. Although this study could not uncover the mechanisms accounting for the observed stabilization, it limits the scope for interpretation to neuromuscular and cognitive perspectives. Based on a fusion of prior findings and the literature available, this section discusses further explanatory approaches, without any claim to be comprehensive.

For the discussion of potential mechanisms, once again it should be highlighted that the results obtained in Chapters 4 and 5 were not caused by the non-clenching task in terms of decreased postural control, but rather by the clenching activity in terms of improved postural control. Therefore, it can be excluded that the effects were simply evoked by an unphysiological state as mandibular rest positions could be. Besides, postural sway reductions were shown to not be evoked by changes on joint coordination and muscular co-contraction level. Hence, other mechanisms that acutely foster motor control must be taken into consideration.

Albeit the different theories might be very different in nature, they basically originate from the assumption that for balance control all subsystems have to be coordinated accurately in a smooth and efficient manner. Therefore, even small intrinsic or extrinsic changes may trigger compensations far from the site of the disturbance, but with impact on whole-body posture. With respect to the CMS, its integration into the postural control system is based on neuroanatomical connections of the N. trigeminus, which were first detected in animals (e.g., Ruggiero et al., 1981; Buisseret-Delmas et al., 1999; Devoize et al., 2010), and were later neurophysiologically confirmed in humans as seen by trigemino-vestibular modulations (Deriu et al., 2003). These findings form the basis for some of the theories postulated to explain the observed phenomena. The respective mechanisms are briefly discussed in the following.

Stiffening hypothesis

As outlined in Subsection 8.1.1, prior research suggested that jaw clenching is accompanied by co-contractions of anterior muscle chains, triggering an increased forward leaning of cranial body segments that, in turn, lead to an anterior shift of the CoP (Hellmann et al., 2011c). Although the hypothesized stiffening of anterior muscle chains was refuted by the kinematic and EMG data in Chapter 4, it might be speculated that stiffening is not limited to the anterior muscle groups, but involves postural muscle per se, irrespective of whether or not the muscles are located anterior or posterior. The rationale behind this assumption is the inverse correlation between stiffening of the body and the variability of the CoP. This phenomenon can be seen in subjects exposed to postural threat, whereat CoP displacements typically decrease as the stiffness increases (Adkin et al., 2000; Carpenter et al., 2001). Hence, it could be speculated that clenching the jaw elicits a stiffening effect that ultimately leads to a reduction of CoP displacements. Given the fact that concurrent jaw clenching did not affect the muscular activities of the lower extremities, stiffening may have occurred in other body parts, e.g., trunk or neck muscles.

One concept supporting the stiffening hypothesis is the assumption that the entire body is biomechanically coupled via myofascial chains (MFC) – groups of muscles that are longitudinally positioned in the human body, connected through fasciae forming a continuous myofascial system (Richardson et al., 2004; Cuccia & Caradonna, 2009; Hellmann et al., 2015). Besides its significance for passive tension distribution, stimulation of the intra-fascial mechanoreceptors might trigger the vegetative and central nervous system to modulate the fascial tension (Myers, 2002). This kind of strain transfer is thought to be transmitted along the MFCs (Schleip et al., 2005; Cuccia & Caradonna, 2009). For instance, this effect was seen in an increased cervical range of motion after lower limb stretching exercises (Wilke et al., 2016). In a similar way, activity of the CMS might be transmitted to the distal muscle groups, altering neck, trunk and lower limb muscle activities and therewith the amount of body sway (Cuccia & Caradonna, 2009; Munhoz & Marques, 2009). However, this explanatory approach is regarded critically (Michelotti et al., 1999; Manfredini et al., 2012; Hellmann et al., 2015). Specifically, even maximal jaw clenching tasks were reported to induce only low co-activation of the neck muscles (Hellmann et al., 2012).

Contrastingly, it could be suggested that stiffening of the body is fostered by the novelty of the clenching task. It is well known that the basic features of mastication, and of chewing in particular, are programmed by the brainstem in the absence of sensory inputs (Lund, 1991). Therefore, chewing essentially is (semi-)automatically driven, lacking the psychophysiological components of motor control. Unfamiliar tasks, however, are indicative of psychophysiological stress, which initially is manifested in increased muscular tension and tonic co-activation of the muscles groups involved (Lundberg et al., 1994). During the later skill acquisition process, this control strategy is sequentially adapted, taking the form of a shift to phasic and selective patterns of muscle activation associated with decreased attentional demands (Carson & Riek, 2001).

Taking the unfamiliarity with submaximal jaw clenching into account, this task might have triggered a robust stiffening of the body that forced the CNS to tighten postural control. At the same time, sensory gain is suggested to be increased, ensuring that sufficient afferent information is available (Cleworth & Carpenter, 2016). In this context, proprioception of the neck muscle could be of great significance. On the one hand, it is known that neck proprioception is an important component of the somatosensory input used by the postural control system (Abrahams, 1977). On the other hand, there is evidence of functional couplings between neck and masticatory muscles (Ertekin et al., 1996; Ehrlich et al., 1999; Yamabe et al., 1999; Eriksson et al., 2000; Haggman-Henrikson & Eriksson, 2004; Hellmann et al., 2012; Hellmann et al., 2015). Furthermore, it has also been shown that occlusal perturbation can modulate proprioception (Gangloff & Perrin, 2002), which in turn could influence balance by modulating co-contraction patterns of trunk and neck muscles (Sforza et al., 2006).

Therefore, it might be speculated that submaximal clenching activities caused stiffening-induced modulations of sensory gain, specifically proprioception of the neck muscles, which finally contributed to provide an improved postural stability. Contrastingly, stiffening of distal muscle groups via MFC seems not be an issue.

Concurrent activation potentiation

Another mechanism being discussed refers to as concurrent activation potentiation. Principally, this mechanism describes the effects remote muscle contractions on neural and distant muscle structures might have. Even though, on a muscular level, this concept seems to act quite similar as a stiffening, it rather relates to the stimulatory effect muscle activations arouse on a neurophysiological level.

These assumptions are based on studies that date back to the early findings of Jendrassik (1885). The author showed that in neurologically impaired patients the strength of reflexes was increased by virtue of the Jendrassik maneuver, i.e., when subjects clenched their teeth and pulled apart their hooked and flexed fingers. Subsequent studies reinforced these effects in different populations, consistently revealing positive interrelations between the Jendrassik maneuver and diverse outcome variables as, e.g., H-reflex, motor evoked potentials and EMG measures (Bussel et al., 1978; Delwaide & Toulouse, 1981; Dowman & Wolpaw, 1988; Pereon et al., 1995; Gregory et al., 2001). Furthermore, it has been demonstrated that even small muscle contractions such as jaw clenching may lead to increased H-reflexes and motor evoked potentials of lower and upper limb muscles, facilitated by an overall enhancement of motor system excitability (Miyahara et al., 1996; Boroojerdi et al., 2000; Takada et al., 2000; Sugawara & Kasai, 2002). In view of this facilitation, this explanatory approach is still frequently employed when researchers aim to explain their findings of bite-induced performance enhancements.

Taking a glance at the main principles and neural processes of postural stability control, it is well-described that balance in quiet stance mainly is based on neural control on subcortical levels (Taube, 2013). On the other hand, balance training studies have shown that improvements of balance skills strongly rely on adaptations and increased involvement of subcortical structures. Concomitantly, balance improvements were associated with reduced cortical contributions as well as decreased spinal reflex excitability; potentially by enhanced supraspinal induced presynaptic inhibition (Taube et al., 2008). Hence, reductions in postural sway are typically coincided with decreased contributions of reflexes to postural stability control.

Conflating the neurophysiologic effects of jaw clenching and the neural processes of postural stability control, a bite-induced facilitation of reflexes that improves the control of balance does not provide a conclusive explanation. Investigations by Tuncer et al. (2007) and Gangloff & Perrin (2002) support this assumption. Whereas latter authors showed postural control to be affected by unilateral anesthesia of trigeminal afferences, Tuncer et al. (2007) found H-reflexes to be facilitated the same whether the teeth were anesthetized or not. Ultimately, latter study suggested that periodontal mechanoreceptors and, in turn, facial proprioceptive input may not play a major role in the facilitation process (Tuncer et al., 2007). Instead, it must be assumed that the observed improvements are reducible to an increased supraspinal excitability. Research supporting this assumption recently was provided by Aboodarda et al. (2015). Albeit the authors applied submaximal contractions of the elbow flexors rather than masticatory muscles, they showed that these voluntary contractions temporarily increased supraspinal excitability whereas spinal excitability was decreased.

The prerequisites for such a potentiation effect are suggested to be associated with cortical mechanisms, including the cortical connection theory or the transcallosal facilitation hypothesis (Ebben, 2006; Ebben et al., 2008). These explanations center around the integrative function of cerebral motor cortex, suggesting a motor overflow between the different areas of the brain, which may lead to an enhanced excitability of adjacent cortical motor areas that finally evoke muscle activations far from the site of the original contraction (Boroojerdi et al., 2000; Ruddy & Carson, 2013). Furthermore, neural pathways with cortical origin, involving an unmasking of excitatory projections and a release of presynaptic inhibition, have been presumed (Sugawara & Kasai, 2002). In this way, remote muscle contractions could facilitate the neural drive to distal muscle groups and amplify the motor output of the prime movers. These modifications might act quite similar to the commonly observed increases in arousal due to higher anxiety or mental stress in order to prepare the body to act (Langlet et al., 2017). This specific arousal effect is related to changes in spinal and supraspinal levels, particularly of corticospinal pathways, which in turn influence the time of information processing and motor execution. That is, more excitable corticospinal pathways are faster to initiate the planned responses (Greenhouse et al., 2017).

As the studies in Chapters 4 and 5 did not apply electroencephalography (EEG), transcranial magnetic stimulation (TMS), functional magnetic resonance imaging (fMRI) or other neurophysiologic methods, this thesis cannot confirm or refute the above-depicted assumptions. Nevertheless, it seems that remote voluntary muscle contractions such as jaw clenching might contribute to facilitations of human motor system excitability, primarily on supraspinal levels, which ultimately increases the neural drive to the distal muscles (Ebben, 2006). Compared to the stiffening hypothesis, therefore, concurrent jaw clenching is supposed to not result in muscular co-contractions but rather to enhance the activation of the targeted muscle groups via neural pathways. This explanatory approach would also be supported by the observational studies described in Subsection 2.5.1. Those studies have shown that activity of masticatory muscle appear as unconscious habits in moments of high physical or mental stress. Therefore, the authors supposed jaw clenching to be incorporated in whole-body movements in the form of a physiological strategy helping to improve the systemic function (Okeson, 1993; Nukaga et al., 2016).

Dual-task paradigm

The final explanatory approach to be discussed refers to the dual-task paradigm. In contrast to the other concepts, which are based on neurophysiological phenomenon and neuronal couplings of the CMS with the postural control system, the theoretical basis for the dual-task paradigm is formed by cognitive approaches and refers to the attentional resources associated with the control of balance.

Traditionally, postural control has been considered an automatic and mainly reflex-controlled task, suggesting that the postural control system requires none or only minimal attentional resources (Woollacott & Shumway-Cook, 2002). Using the dual-task paradigm, researchers were able to refute this assumption. When challenging subjects to concurrently perform a postural control and a secondary motor or cognitive task, the sensitivity of postural control to cognitive manipulations became apparent (Lajoie et al., 2016). Within this framework, even highly practiced postural tasks, such as quite standing and walking, were shown to require some attentional requirements, inferred by a decline on the secondary task (Lajoie et al., 1993; Shumway-Cook et al., 1997). The degree of processing was shown to vary depending on the subject's age and balance skills as well as on the difficulty of the postural task (for review, see Woollacott & Shumway-Cook, 2002).

Within the studies described in Chapters 4 and 5, the participants were asked to balance in upright unperturbed stance and to concurrently control and adjust their bite force by means of a visual real-time feedback. It must be assumed that postural control – due to the high attentional demands associated with submaximal biting – became the secondary task, subject to change during the performance of the concurrent biting task (Woollacott & Shumway-Cook, 2002). In latter case, attentional costs would be reflected in performance changes on the postural task, taking the form of decreased postural sway. The rationale behind this decrease is the increasing automatic character of postural control when attentional demands for the concurrent task increase. Especially continuous secondary tasks are sufficient to suppress conscious attendance to postural control, facilitating a more automatic control (Polskaia et al., 2015; Lajoie et al., 2016). In consequence, an enhanced stability while performing the concurrent task as opposed to a single-task condition can be observed.

Taking the aforementioned into account and concerning the attentional demands associated with continuous jaw and fist clenching, one must pose the question whether the effects observed were merely the result of dual-task interferences. Specifically, jaw clenching could have permitted attention to be withdrawn from the postural task and therefore could have reduced postural sway due to the increase in automatic control. As stated in Chapter 4, the authors were well aware that secondary tasks could affect postural stability differently. Therefore, subjects were asked to keep their mandible in a resting position and to consciously apply no bite force, monitoring this condition by looking at the feedback screen. However, it cannot be excluded that the attentional demands for the control condition were comparable to the submaximal clenching tasks, particularly since mandibular rest position is mainly (semi-)automatically controlled by the CNS, whereat the stereotypical motor activity probably lacks the cognitive components.

8.2 Dynamic postural control is not affected during concurrent jaw clenching

The studies reported in Chapters 4 and 5 have demonstrated the influence of concurrent jaw clenching on static postural control during unipedal and bipedal stance as well as for standing on firm and foam surfaces. A significant decrease in CoP displacements induced by submaximal isometric bite forces has been revealed in conjunction with decreased sway of cranial body segments. These sway reductions were accompanied by systematic reductions of joint motions of the lower extremities, however, without causing alterations of the basic postural strategies. Relating to the prevailing view that increased postural sway indicates a deterioration of balance control, both experiments provide evidence that remote muscle contractions in general, and jaw clenching in particular, might contribute to enhance static postural stability.

Despite the mostly consistent findings towards these stabilizing effects, previous studies have focused almost entirely on the influence of mastication and clenching on postural control under static conditions. Only little has been reported about the effects of concurrent clenching on dynamic postural stability, which is maintaining or recovering balance in response to internal or external disturbances. Investigations under dynamic conditions are of particular relevance, however, especially since dynamic stability is much more related to the risk of falling than static stability (Rubenstein, 2006).

The study described in Chapter 6 concerned this issue and investigated the effects of submaximal jaw clenching on dynamic stability in response to forward loss of balance. By this means, the objective of this study was to extend the findings of the first two experiments and to further evaluate whether similar effects would result for reactive balance. The methodological approach applied in this study comprised a simulated forward loss of balance, which was chosen as it involves components of postural control but also muscular strength and reaction time, which were found to be positively influenced by remote voluntary contractions as well (Forgione et al., 1991; Miyahara et al., 1996; Takada et al., 2000; Hiroshi, 2003; Ebben et al., 2008). Therefore, it was hypothesized that concurrently clenching the teeth would also improve balance recovery. The results showed that the jaw clenching task did not result in ergogenic effects as it did for static stability. In particular, neither the dynamic stability measures nor the joint angles of the lower extremities were significantly affected by the jaw motor activity. Furthermore, this study confirmed that the subjects' dynamic stability was not associated with their static stability values depicted in Chapter 4.

The statistically non-significant associations between static and dynamic postural control are consistent with the current literature (e.g., Shimada et al., 2003; Granacher et al., 2011a), suggesting that static and dynamic postural control represent task-specific sensorimotor skills that are differently controlled by the postural control system (Granacher et al., 2011a). Based on this assumption, it could be speculated that the discrepancies between the results in Chapters 4 and 6 were evoked by the different motor demands associated with upright unperturbed stance on the one hand, and balance recovery after simulated forward falls on the other hand. More precisely, the former primarily relies on unconscious and automated feedback mechanisms (Horak, 2006), whereas the latter requires huge demands on explosive muscle activation and an adequate stepping response, which mainly follows feedforward control (Karamanidis et al., 2008). This distinction is a particular issue of concern, not only for abovementioned correlations but also for the interpretation of the observed data.

In Subsection 8.1.3, stiffness-induced increases in sensory gain and facilitation of motor system excitability associated with enhanced neural drive to distal muscles were considered potential mechanisms to explain the stabilizing effects of submaximal clenching under static conditions. In the scenario of simulated forward falls, wherein subjects can anticipate the forthcoming fall and therefore can preselect their postural responses, these aspects might not be an issue. Furthermore, one must assume that the initial forward leaning position along with the expectation of the forward loss of balance significantly increased the subject's anxiety, which in turn may have enhanced the arousal and premotor muscular activity. Hence, the methodological approach applied might undermine the ergogenic effects commonly described. On the other hand, one could argued that more ecologically valid experiments representing realistic fall situations would have revealed differing results. Herein, subjects are unware of the falling event and balance recovery primarily is based on stereotypic reflexes and compensatory movements. Relating to the hypothesized mechanisms, unexpected everyday scenarios thus might expose the ergogenic effects of concurrent clenching activities.

Previous studies assessing reactive balance in response to unanticipated force plate translations or unilateral electrical stimulation of lower limbs support this assumption. Those studies found latencies of postural responses to be significantly increased with lower jaw relaxed than those while chewing gum (Kaji et al., 2012) or submaximal clenching the teeth (Hosoda et al., 2007; Fujino et al., 2010). Altogether, these findings corroborate the results concerning static postural stability, suggesting that jaw motor activity could contribute to maintenance of postural stability during unperturbed stance as well as to recovery of balance when transient and sudden perturbations appear. The study in Chapter 6 cannot support this facilitation, however.

As briefly depicted above, this discrepancy likely has methodical reasons. Although the subjects were randomly released within a timeframe of five seconds, it must be assumed that the awareness of the upcoming fall increased both the motor system's excitability and the amount of voluntary movement control. Apart from that, the experimental approach could be tainted with a sensitivity problem. First, in healthy subjects there might be a ceiling effect since the perturbation is not difficult enough. Second, other variables such as muscular strength, step length and velocity have been identified as influential factors for dynamic stability in balance recovery tasks (Karamanidis et al., 2008; Carty et al., 2012; Graham et al., 2014). And third, the applied method and its criteria might not be able to distinguish between different experimental conditions within homogeneous populations. Albeit, there are some studies that have shown to evince postural deficits using this experimental approach, those studies compared stability values between populations of different ages or between healthy and disabled persons (Wojcik et al., 2001; Karamanidis & Arampatzis, 2007; Arampatzis et al., 2008; Karamanidis et al., 2008; Curtze et al., 2010; Graham et al., 2014).

Taken together, the questions arises whether (i) the results obtained are the consequence of the methodological approach or (ii) the stabilizing effects of concurrent jaw clenching are limited to static postural control. Unfortunately, these questions cannot be answered by the present thesis. Future studies would have to contrast the effects of submaximal biting under conduction of sudden and random perturbations, preferably in diverse populations.

Apart from the lack of influence on dynamic postural stability, the study yielded another interesting finding. For both submaximal clenching and non-clenching conditions, a significant increase of bite forces from initiation until recovery of the fall were found. Concerning this spontaneous activity, clenching the jaw might be incorporated habitually in motor control during strenuous situations. These findings furthermore imply that an open-mouth, non-clenching condition might be an unphysiological state, which is not preferred during challenging situations. This is consistent with several observational and neurophysiologic studies (Sections 2.5 and 2.6) and emphasizes that clenching the jaw might be part of a common physiological repertoire used to enhance the motor performance in many ways. Out of this findings, it is suggestable that many studies that assessed the effects of jaw clenching actually did not observe performance improvements when the jaw was clenched but rather a decrease of performance during the non-clenching condition (Hiroshi, 2003; Ebben et al., 2008).

8.3 Golf performance is not affected by concurrent jaw clenching

Increasing attention has also been focused on athletic performance and the potential benefits of oral appliances. These devices are primarily used to properly align the mandible to achieve an effective physiologic state. Whereas some studies confirmed the ergogenic effects resulting from use of jaw-aligning appliances, e.g., in measurements of muscle strength (Forgione et al., 1991; Forgione et al., 1992; Gelb et al., 1996; Arent et al., 2010; Dunn-Lewis et al., 2012; Kaufman & Kaufman, 1985), other studies failed to prove any influence (Cetin et al., 2009; Allen et al., 2014; Golem & Arent, 2015). Latter results are reinforced by weak experimental designs and a lack of control conditions in some of the former studies (Jakush, 1982; McArdle et al., 1984). Additional support comes from studies using double-blind tests, claiming that performance enhancements are simply a results of placebo effects (Burkett & Bernstein, 1983; Allen et al., 1984; McArdle et al., 1984; Chiodo & Rosenstein, 1986).

Similarly, there is a controversy towards the effects of oral appliances on the performance of professional golf players. Some researchers have shown that the use of an adjusted oral splint may aid to optimize the driving distance and club head speed (Kwon et al., 2010; Pae et al., 2013). As the oral splint did not change initial ball speed and putting accuracy (Pae et al., 2013), it was assumed that these improvements were the result of an enhanced muscle strength rather than an increased focus of attention. A study by Egret et al. (2002), however, did not report any changes in average ball speed and kinematic pattern of the golf swing, although a reduction of ball speed variability was found. Some weak points of these studies – which also might have contributed to the prevailing controversy – are the lack of information concerning the generated bite forces and the mandibular positions during the experiments. In particular, mostly the actual oral motor activity while wearing the splints remained unknown (Allen et al., 2014). Other studies used simple over-the-counter appliances that altered jaw relation to an undefined position (Golem & Arent, 2015).

Given the consistent findings towards the ergogenic effects of jaw clenching along with the lack of investigations on the effects of jaw clenching on golf performance, the study described in Chapter 7 addressed this gap of knowledge. Specifically, this study comparatively examined the effects of submaximal biting on an oral splint, submaximal clenching one’s teeth and habitual jaw position on shot performance and impact variables for golf shots over different distances.

The study revealed that neither shot precision and shot length nor impact variables were systematically influenced by the jaw clenching tasks. Hence, biting on the oral splint did not affect golf performance differently from biting on one’s teeth or habitual jaw positioning. These findings reinforce the doubts towards the potential performance benefits of jaw-aligning appliances. On the other hand, they contradict a number of reports that have described the ergogenic effects of clenching activities (e.g., Ebben, 2006; Allen et al., 2016). Latter might be caused by the coordination-demanding task of the golf swing per se. Although it has been stated that driving distance is closely related to muscle strength of the upper and lower extremities (Hellström, 2009), golf swings are not just simple strength-related single-joint movements but rather coordination-demanding full-body motions. Golfers usually try to increase the torque applied to the club by summation of speed on the basis of successive actions of the hip, trunk and shoulders, followed by motion of the arms, wrists and hands (Burden et al., 1998; Egret et al., 2002). In turn, one must question to what extent golf swings actually depend on muscle strength of the limbs, and whether modulation of motor system excitability and improvements in prime mover muscle activity in this context could be a decisive factor.

Interestingly, as in the study reported in Chapter 6, the subjects even under habitual conditions clenched their teeth while performing the golf shots. This underpins the assumption that clenching the jaw could be implemented in human motor control as an unconscious physiological strategy used to enhance performance. This would indicate that previous studies did not observe strength improvements during remote muscle contractions but rather a decrease while subjects were non-clenching (Hiroshi, 2003; Ebben et al., 2008). Unfortunately, this study did not assess the golfers' performance while having their mouth opened. According to Egret et al. (2002), professional golfers cannot easily perform golf swings with an opened mouth. Hence, it must be assumed that golf performance is decreased under such conditions. The study also did not assess the golfers' performance while wearing the splint under habitual jaw motor activity. This would shed further light onto the potential effects of oral appliances on human motor performance. For instance, the simple application of oral splints – without generating bite forces – could foster the athletes' performance. This possibility cannot be completely excluded. However, in view of the presented findings and the literature available, beneficial effects of oral appliances on human motor performance seem unlikely.

In summary, it must be stated that neither submaximal teeth clenching nor biting on the oral appliance did superiorly affect golf performance compared with a habitual control condition. Recommendations concerning the use of bite-aligning splints and concurrent clenching activities for performance enhancement are therefore questionable. Conversely, clenching the jaw and usage of the oral splint also did not impair the athletes' golf performance. Essentially, particularly in high-level sports, the athlete and potential intervention to improve performance should always be regarded individually.

8.4 Implications and recommendations

The findings presented and discussed in this thesis virtually reflect the prevailing controversy concerning the interrelation of the craniomandibular system with the postural control system. Likewise, the thesis underpins the uncertainty regarding the potential advantage of oral appliances and jaw clenching with respect to sports performance. Whereas jaw and fist clenching were shown to gain stabilizing effects in simple and challenging upright stance, the studies assessing balance recovery and golf performance did not find any significant alterations in postural stability and performance measures, respectively. In view of the yet remaining contradictions and the sparse literature available, further research is necessary to replicate and enhance the findings reported here. Against this background, it is highly important to enlarge the overall study situation by providing valuable and methodologically sound studies in order to establish a broader consensus and clear evidence concerning the mutual relations between craniomandibular and postural control systems.

Besides the investigation of clenching effects on a behavioral level, the present thesis conducted comprehensive biomechanical analyses aiming to elucidate the causes accounting for this interference. The presented studies could not entirely clarify the underlying mechanisms, however. A specific focus of attention in future studies should therefore be given to the identification of the mechanisms responsible for the potentiation induced by clenching activities. This may include experiments encompassing neurophysiologic methods to identify the sites and pathways of the facilitation (concurrent activation potentiation) or studies that compare the effects of clenching with different secondary motor or cognitive tasks (dual-task paradigm). Apart from that, future studies should consider the following issues:

- assessment of jaw clenching effects on dynamic postural stability under conduction of random perturbations and in different populations;
- examination of changes and re-weightings in postural muscles synergies induced by clenching activities;
- investigation of the impact and the suppression of jaw clenching in diverse sports and activities of daily living in order to examine its functional significance;
- identification of further muscles whose activation may facilitate human motor control and performance, e.g., site of activity, amount of activity, temporal structure;

- comparison of intra-oral splints and jaw-aligning appliances with natural teeth clenching to evaluate the significance of oral appliances in this context;
- investigation if occlusal conditions such as (myo-)centric relation or intercuspation could foster or hinder the virtue of jaw clenching;
- consideration of the long-term effects of clenching to ascertain whether the gains evoked by clenching were only due to the novelty of the task.

9 Conclusion

The control of human posture and balance is fundamental for most activities of daily living and therefore in many disciplines an essential field of research, possessing great significance for theoretical and practical reasons. On the other hand, the enhancement of recreational and competitive athletes’ performance is vital for coaches and athletes, and of particular interest for sports scientists.

Both issues – postural control and sports performance – were considered in this thesis, with special attention being paid to the impact of concurrent clenching activities. Therewith, this thesis provides valuable research combining fundamental aspects of human motor control and performance with practical issues regarding the potential advantage of concurrent clenching activities. Beyond that, the vulnerability of the human motor control system to internal neuromuscular modifications was pointed out. These features are well in the scope of current research, although literature regarding the interaction of human motor control and performance with the CMS is relatively sparse. This implies manifold unresolved research questions and the requirement of sufficient scientific evidence.

The present thesis aimed to overcome these research gaps and to gain a more detailed insight into the mechanisms underlying a potential interference. For this purpose, biomechanical analyses encompassing posturographic measurements, 3D motion capturing, and electromyographic analyses were applied to examine changes on CoP, kinematic, and muscular levels. Furthermore, radar-based techniques were used to estimate golf performance during clenching and to assess the potential benefit of oral appliances in golf sports. Essentially, the research articles presented in this thesis revealed the following findings:

(i) Concurrent clenching of the jaw at a submaximal bite force increased static stability, which was indicated by significant reductions of CoP displacements and decreased oscillations of cranial body segments. These gains coincided with decreased angular motions about the lower extremity joints, whereas postural control strategies remained unaffected. The stabilizing effects of jaw clenching were also not related to alterations in mean activation and co-contraction variability of the lower extremity muscles. Presumably, clenching increased static stability by improving the kinematic precision among neuromuscular control patterns. This effect is either of neural (concurrent activation potentiation) or cognitive origin (dual-task paradigm).

(ii) Fist clenching evoked similar reductions in postural sway as jaw clenching compared to a habitual control condition, both on firm and foam surfaces. Consequently, the improvement of static postural stability was not an exclusive jaw clenching effect but rather the result of concurrent clenching activities in general. Therefore, neuroanatomical connections between the CMS and structures involved in the postural control process do not appear to play the dominant role for this facilitation.

(iii) Voluntary clenching the jaw did not help to improve dynamic stability when recovering from forward loss of balance. In addition, joint kinematics of the lower extremities were unaffected under these conditions. A critical reflection of the experiment suggests that these finding could be affected by the methodology applied. The assessment of dynamic stability in form of simulated forward falls suppresses large proportions of compensatory postural responses. Furthermore, the task itself already increases the subject's arousal and therewith the premotor muscular activity. Hence, the methodological approach applied here probably undermined the mechanisms typically used to describe the effects of concurrent clenching activities. The findings of this study should therefore be viewed with caution, longing for ecologically valid experiments representing sudden realistic fall situations.

(iv) Neither biting on one's teeth nor the application of oral splints in conjunction with jaw clenching improved the performance of competitive golfers with respect to driving distance, shot precision and impact variables. On the other hand, both study conditions chosen did not have an adverse impact on the athlete's golf performance compared to golf shots with habitual jaw position. Essentially, particularly in high-level sports, the athlete and potential interventions to improve performance should always be regarded individually. Notwithstanding this, it remains unclear whether the usage of oral splints could provide differing results when subjects are not forced to clench their teeth but rather maintain habitual jaw relations.

Taken together, the present thesis adds some valuable work to the literature, reinforcing the bulk of prior findings and expanding on them by proving the impact of jaw clenching to apply also for more challenging static balance tasks. Moreover, this thesis points out the general potentiation of motor control through concurrent remote voluntary contractions that finally could gain the human an advantage in manifold ways. As previous studies along with the experiments in Chapters 6 and 7 have shown, this activation of remote muscle groups appears to be part of a physiological strategy, which in a habitual manner may be implemented in motor control to increase the neuromuscular arousal. In turn, this strategy might increase human motor performance, especially in moments of high physical or mental stress. Concurrently, this habitual and spontaneous occurrence of masseter muscle activity during balance recovery and golf swing could have suppressed the ergogenic effects described for static postural stability. Therefore, it needs to be clarified whether the methods applied in those studies could have contributed to the inconsistent findings.

Concerning previous studies in the context of dynamic stability and jaw clenching, clear benefits of jaw clenching with respect to balance recovery had been confirmed (Hosoda et al., 2007; Fujino et al., 2010). Despite the same intention, the usage of different methodological approaches, that is fall simulation compared to unanticipated force plate translations or electrical stimulations, has led to the diverging outcomes. Hence, future studies should carefully select their methodological approaches, bearing in mind the plethora of factors influencing human postural control and motor performance.

In conclusion, postural control and sports performance are essential and interdisciplinary fields of research, both from fundamental and applied research perspectives. Sports scientists but also researchers from adjacent disciplines, such as medicine, human movement science, or neuroscience have provided vital information to the understanding of the features and mechanisms of postural control and sports performance. Albeit the present thesis could not finally uncover the mechanisms responsible for the observed facilitation, this thesis makes a valuable contribution to this sparsely investigated field of research and gains a deeper insight into the habits, interrelations and opportunities of jaw clenching activities with respect to human motor control and performance. In view of the current literature, for this interrelation diverse mechanisms must be taken into consideration, encompassing, e.g., stiffening-induced increase of sensory gain, concurrent activation potentiation resting on cortical excitation and automation of postural control via dual-task effects. To comprehensively assess the potentials of remote voluntary contractions and to profoundly enlighten the site of this neurophysiologic phenomenon, further research must be conducted.

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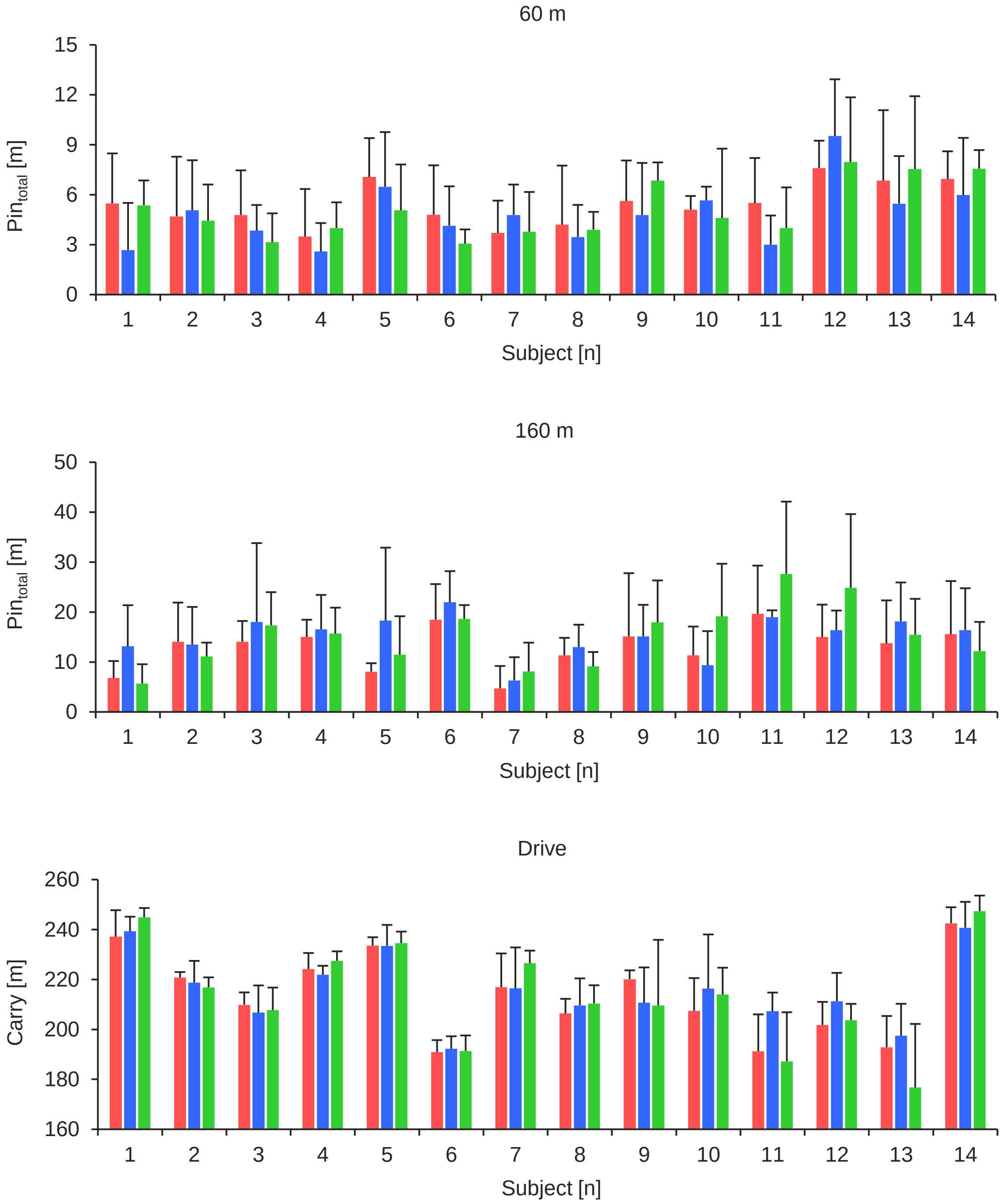
Appendix

Supplementary Material

S1 The table lists the thirty-nine markers, which were placed on the skin to the participants in accordance with the Vicon Plug-in Gait full body marker set (Vicon Motion Systems, 2010).

Head			
LFHD	Left front head	RFHD	Right front head
LBHD	Left back head	RBHD	Right back head
Torso			
C7	7th cervical vertebrae	CLAV	Clavicle
T10	10th thoracic vertebrae	STRN	Sternum
RBAK	Right back		
Pelvis			
LASI	Left anterior superior iliac spine	RASI	Right anterior superior iliac spine
LPSI	Left posterior superior iliac spine	RPSI	Right posterior superior iliac spine
Upper limb			
LSHO	Left shoulder	RSHO	Right shoulder
LUPA	Left upper arm	RUPA	Right upper arm
LELB	Left elbow	RELB	Right elbow
LFRA	Left forearm	RFRA	Right forearm
LWRA	Left wrist marker A	RWRA	Right wrist marker A
LWRB	Left wrist marker B	RWRB	Right wrist marker B
LFIN	Left fingers	RFIN	Right fingers
Lower limb			
LTHI	Left thigh	RTHI	Right thigh
LKNE	Left knee	RKNE	Right knee
LTIB	Left tibia	RTIB	Right tibia
LANK	Left ankle	RANK	Right ankle
LTOE	Left toe	RTOE	Right toe
LHEE	Left heel	RHEE	Right heel



S2 Intra-individual und inter-individual comparisons of golf performance for 60 m, 160 m and Drive as functions of oral motor tasks, quantified by $\text{Pin}_{\text{total}}$ and Carry, respectively.
$\text{Pin}_{\text{total}}$ = total distance to pin; Carry = shot length; B_T = biting on teeth; B_S = biting on splint; HJP = habitual jaw position

Statutory Declaration

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

> „Effects of Concurrent Jaw Clenching on Human Postural Control and Sports Performance – Biomechanical Studies of Static and Dynamic Postural Control and Performance Analysis in Golf"

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 14. Mai 2018