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PERSPECTIVE

Human motor performance assessment with lower limb exoskeletons as a potential strategy to support healthy aging—a perspective article

Tobias Moeller[1,*], **Melina Beyerlein**[1], **Michael Herzog**[1], **Bettina Barisch-Fritz**[1], **Charlotte Marquardt**[2], **Miha Dežman**[2], **Katja Mombaur**[2], **Tamim Asfour**[2], **Alexander Woll**[1,3], **Thorsten Stein**[1,3] **and Janina Krell-Roesch**[1,3]

[1] Institute of Sports and Sports Science, Karlsruhe Institute of Technology, Karlsruhe, Germany
[2] Institute for Anthropomatics and Robotics, Karlsruhe Institute of Technology, Karlsruhe, Germany
[3] These authors contributed equally to this work.
[*] Author to whom any correspondence should be addressed.

E-mail: tobias.moeller@kit.edu

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Abstract

With increasing age, motor performance declines. This decline is associated with less favorable health outcomes such as impaired activities of daily living, reduced quality of life, or increased mortality. Through regular assessment of motor performance, changes over time can be monitored, and targeted therapeutic programs and interventions may be informed. This can ensure better individualization of any intervention approach (e.g. by considering the current motor performance status of a person) and thus potentially increase its effectiveness with regard to maintaining current performance status or delaying further decline. However, in older adults, motor performance assessment is time consuming and requires experienced examiners and specific equipment, amongst others. This is particularly not feasible in care facility/nursing home settings. Wearable robotic devices, such as exoskeletons, have the potential of being used to assess motor performance and provide assistance during physical activities and exercise training for older adults or individuals with mobility impairments, thereby potentially enhancing motor performance. In this manuscript, we aim to (1) provide a brief overview of age-related changes of motor performance, (2) summarize established clinical and laboratory test procedures for the assessment of motor performance, (3) discuss the possibilities of translating established test procedures into exoskeleton-based procedures, and (4) highlight the feasibility, technological requirements and prerequisites for the assessment of human motor performance using lower limb exoskeletons.

Abbreviations

5STS	Five Times Sit-to-Stand test
ADL	activities of daily living
BBS	Berg-Balance Scale
CoM	center of mass
DoF	degrees of freedom
FICSIT-4	Frailty and Injuries: Cooperative Studies of Intervention Technique
FMG	force myography
FSR	force sensing resistor
GRF	ground reaction forces
IMU	inertial measurement unit
POMA-B	Tinetti Performance-Oriented Mobility Assessment
RoM	range of motion
sEMG	surface electromyography
SGB	strain gauge bridge
TUG	Timed Up and Go test

1. Introduction

Societies around the world are experiencing increasing longevity and population aging, often due to better access to health care, favorable changes in the nature of (manual) labor, and improved socio-economic status of older individuals [1]. A recent report by the United Nations [1] estimated that the number of 771 million persons aged ⩾65 years today will increase to 1.6 billion persons by 2050 (one sixth of individuals worldwide).

With increasing age, there is a decline in cognitive [2] and motor performance [3], which accelerates in the last years of life [4]. Motor performance deficits in old age include but are not limited to compromised postural stability and gait, and decreased muscle strength [5]. However, there is also large heterogeneity of motor performance in older adults, i.e. the difference between individuals who experience a rapid versus slow decline in motor performance becomes most apparent in old age ('fitness gap') [6]. Furthermore, the prevalence of multiple chronic diseases (i.e. medical comorbidity), such as Parkinson's disease, or osteoporosis, increases with age, and in turn correlates with decreased motor performance and increased disabilities [7, 8].

Lower levels of motor performance are associated with an increased risk of mortality in community-dwelling older persons [9]. In addition, decreased levels of lower extremity function in older adults are related to higher frequency of impairment in ADL and mobility-related disability [10]. In light of the large heterogeneity and inter-individual differences of both magnitude and speed of motor performance changes in older adults, it is important to provide persons with individualized exercise training based on their current motor status [11]. However, this is particularly challenging in settings with limited financial, personnel, or material resources, such as nursing homes, rehabilitation centers, or residential/in-home care facilities. To this end, the development and use of exoskeletons, not only for motor performance assessment but also for training, may offer a way to overcome some of these challenges and limitations [12]. To date, exoskeletons are developed mainly for occupational physical support and rehabilitation of individuals with movement or mobility impairments (e.g. due to spinal cord injuries or stroke), but may also be used to provide support during exercise training and everyday use in older adults [12]. In addition, it is conceivable that exoskeletons may be used to comprehensively assess motor performance in older adults, e.g. through built-in sensors [13, 14].

Despite significant advancements in exoskeleton research, there are still challenges concerning their proper use among older adults. For example, from a sports science and clinical perspective, it is critical that the technology supports older individuals as much as necessary (e.g. provide stability when a fall is imminent), but also as little as possible (assist-as-needed) in order to avoid facilitating motor performance decline. If used appropriately, exoskeletons may be effective in maintaining a person's current level of motor performance or achieving training effects, e.g. a slowed decline or even subtle increase in motor performance over time [15, 16].

An individualized control mechanism and training, however, requires an assessment of the user's current level of motor performance before and/or during exoskeleton use. To this end, the built-in sensors of the exoskeleton could be used for motor performance assessments, e.g. by conducting established or newly developed motor performance tests while wearing an exoskeleton, and measuring the amount of support needed. It is known that, due to the close proximity and direct connection to the body, exoskeletons can capture human movement [17]; thus, we hypothesize that sensors may also be used to assess human motor performance. Such exoskeleton-based assessments of motor performance may be more specific and sensitive, even to very early or subtle motor performance changes, and especially as compared to traditional, validated and well-established assessments used in clinical, or home-based settings. Furthermore, these exoskeleton-based motor performance assessments could provide better standardization and reliability, and allow the assessment of motor performance of individuals with motor disabilities or very low motor performance over a prolonged time [14, 18]. In an initial review [14], we were able to show that few studies to date have used exoskeletons for lower limb motor performance assessment, albeit with many limitations and gaps (e.g. regarding the optimal design of the exoskeleton to measure human motor performance, the impact of the exoskeleton on human motor performance, the lack of exoskeleton-based balance assessment) that need to be addressed in future research. Similarly, in another review [13] focusing on clinical motor performance assessments using robots, the authors conclude that robot-supported assessments still represent a 'green field', and new approaches should be developed.

To address the gaps identified in few prior studies and literature reviews as outlined above, we here aim to provide recommendations and potential preliminary guidelines for exoskeleton-based human motor performance assessments derived from interdisciplinary perspectives and view points. Specifically, we focus on selected motor skills and functions that are relevant to aging and may be assessed using exoskeletons. To this end, we describe as to how these assessments can be conducted, thereby also addressing necessary technical requirements and challenges that would need to be overcome in the future. We postulate that exoskeleton-based motor performance assessments may become more widely used in the long-term, if and when next-generation exoskeletons with fewer limitations and assist-as-needed control strategies will become available. The manuscript is structured as follows: First, we provide a brief overview of age-related changes of motor performance, and summarize established test procedures used in clinical and laboratory settings to assess motor performance. Second, we briefly present the current state of research on the use of lower limb exoskeletons to assess motor performance and describe potential approaches for exoskeleton-based motor performance assessments. Finally, we describe technological requirements and prerequisites for the successful use of lower limb exoskeletons to assess motor performance.

2. Motor performance in older adults

Due to their high relevance for maintaining independence and quality of life in old age, we focus on changes in different motor performance abilities and skills related to the lower limbs that occur during the normal aging process, namely (1) gait, (2) posture, (3) muscular strength, and (4) proprioception. Of note, these motor abilities and skills should not be regarded as distinct but rather as interrelated constructs [19]. This section covers an overview of motor abilities and skills, their importance for older adults, and age-related changes.

2.1. Gait

Human locomotion is critical to transport the CoM from one point to another by using a bipedal gait in the most efficient way [20]. With increasing age, gait disorders become more likely, caused primarily but not exclusively by health-related conditions such as musculoskeletal, affective, sensory, or neurological disorders [21, 22]. Specific age-related gait changes are a decrease in stride length, an increase in stride width, stance phase time and energy expenditure, as well as alterations in joint kinematics and kinetics, amongst others [21, 23, 24]. The most common gait-related change in old age is reduced gait speed (mean walking speed in healthy older adults $>$60 years: 1.2 $\mathrm{m\,s^{-1}}$), whereby a speed of 1 $\mathrm{m\,s^{-1}}$ or less is considered abnormal, and less than 0.4 $\mathrm{m\,s^{-1}}$ is associated with problems in carrying out ADL [25, 26].

2.2. Posture

The control of posture is crucial to perform everyday tasks. Posture comprises two components, i.e. orientation and balance, and is regulated continuously based on different sensory inputs such as vestibular, visual, or proprioceptive information [27, 28]. Human balance is often defined as a multidimensional concept of 'the ability of a person not to fall' [29]. To this end, during standing, the individual needs to keep the downward projection of the CoM within the base of support, an area defined by the body parts in contact with the environment. According to Pollock and colleagues [29], postural control is essential for maintaining balance in three main classes of human action: (1) maintenance of the current position (static steady state); (2) voluntary movements (dynamic predictive/dynamic steady state); and (3) response to an external disturbance (dynamic reactive). Depending on how static and dynamic balance is challenged, different sensory channels are more active than others, and different strategies (i.e. ankle, hip or step strategy) to react to perturbations are used [28, 30]. Due to various age-related changes in the musculoskeletal (e.g. lower strength and RoM), and sensorimotor control (e.g. poorer vision), balance performance in all three classes decreases during aging [30, 31]. Balance performance also tends to decrease more when more than one sensory system is demanded in dynamic and unstable situations [32]. Compared to younger adults, older adults react to balance challenges by applying a more hip-based strategy to maintain or restore balance in dynamic situations [31]. Furthermore, low balance performance in older individuals is associated with higher risk and occurrence of falls [33]. One in three individuals aged ⩾65 years experience one or more falls per year [34]. Falls have a negative impact on various health outcomes, including an increased risk of injury and hospitalization [35], poorer mental well-being [36] or an increased risk of mortality [37].

2.3. Muscular strength

Human muscular strength is the ability to exert force or torque [38]. Strength can be applied in many different forms, such as isometric, isokinetic, or isotonic. Muscular strength is determined by a combination of factors, including muscle size and mass, muscle architecture, neural activation, and neuromuscular inhibition [39]. Smaller muscle size, often measured as cross-sectional area, is strongly associated with decreased strength [40]. In addition, neural factors, such as motor unit recruitment, firing frequency, synchronization, and increased inhibition can decrease strength, even without changes in muscle size [41]. Muscular strength in older adults is critical for carrying out ADL, recovering from falls, and maintaining independence [42, 43]. With increasing age, the number of motor units decreases, along with changes in their morphology and properties [44]. Combined with an age-related loss of muscle mass or sarcopenia, these changes lead to a reduced muscular strength, which is a well-known risk factor for mortality, falls, disabilities, loss of independence, and quality of life [45, 46]. It has been postulated that the decline of muscular strength begins during the fifth or sixth decade of human life [47].

2.4. Proprioception

Proprioception refers to the sense of body position and motion [48]. It is important for planning and executing precise movements and is closely related to posture, gait, and performing ADL [49, 50]. To detect body position and motion, the human body uses different mechanoreceptors such as the muscle spindles, or Pacinian corpuscles [51]. These signals are then processed in the central nervous system and provide input for the planning and execution of movements [52]. With increasing age, proprioception declines mainly due to changes at both, central and peripheral levels. At the peripheral level, structural changes of the muscle spindle lead to a decreased performance to detect the body's current state, and a decreased performance. At the central level, there is an age-related degeneration of nerve cells, as well as neurochemical changes [53]. These changes lead to greater body sway, increased co-activation of antagonists, and less impact on the proprioceptive sense to maintain or increase postural control. The influence of the visual sense increases during aging because of decreasing proprioception which is critical for balance and gait [54].

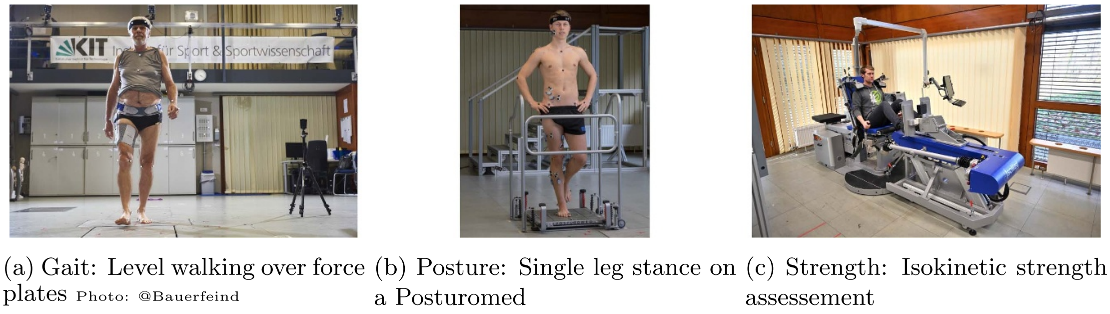
3. Established motor performance assessments in older adults

Motor performance assessments in older adults are mostly conducted in clinical and/or care facility settings to determine required support, inform training/rehabilitation recommendations, as well as in laboratory settings for research and in-depth diagnostic purposes. Both settings and approaches differ concerning requirements for motor performance testing, and assessments used in either setting have advantages and disadvantages with regard to the time needed for administration and evaluation of obtained results, personnel, and material requirements, or sensitivity and specificity [55, 56]. For example, assessments used in clinical, or nursing home/care facility settings, can often provide information on the current status of motor performance parameters, declines over time, or training-related increase [55, 56]. In addition, laboratory assessments may also be used to identify potential underlying causes of motor performance decline, e.g. age- or disease-related processes. Examples of tests used in laboratory and field settings are provided in figures 1 and 2. Thus, when selecting appropriate motor performance assessments, one should consider various factors, including but not limited to the target population, the goal of the measurement, the parameters to be measured, and the psychometric properties of the assessment [57].

In the following sections, we provide a brief overview of assessments to assess lower limb motor performance abilities and skills critical for older adults as mentioned above. Please also refer to table 1 for a summary of these assessments, including information about psychometric properties, and our evaluation of the feasibility of converting these tests into exoskeleton-based tests, along with potential necessary prerequisites (please refer to sections 4 and 5).

3.1. Gait assessment

Different gait assessments are described in the literature, and they can be distinguished depending on the goal and desired outcome parameters, or the precondition of the individuals to be tested. In nursing



(a) Gait: Level walking over force plates Photo: @Bauerfeind (b) Posture: Single leg stance on a Posturomed (c) Strength: Isokinetic strength assessement

Figure 1. Laboratory motor performance tasks.

(a) Gait: Timed Up and Go test (TUG) (b) Posture: Tandem Stance (c) Strength: Sit to Stand Test

Figure 2. Clinical/functional motor performance assessments.

home/care facility settings, the TUG is a widely-used test to assess mobility and risk of falls. Individuals who require less than 20 s to complete the task are considered mobile enough to lead an independent life. Those who take more than 30 s to complete or are unable to do the task are considered to have reduced mobility and may need assistance with ADL [58]. An instrumented TUG version also exists, i.e. the individual carries out the test while being equipped with sensors (e.g, IMU) to additionally collect data [59].

In addition, distance-based walking tests (usually between 2.4 m and 25 m) are commonly-used gait tests for older adults. Walking speed, particularly during short distances, is regarded as a predictor of the ability to perform ADL, and mortality [60, 61]. Distance-based walking tests have good validity and test-retest reliability; however, their implementation is not standardized and comparability across different research studies is thus limited [62]. Besides distance tests, timed tests like the Two- or Six-minute walking test are common. These are considered as sub-maximal aerobic tests mainly for cardiovascular patients or endurance assessment, but are not discussed further in this manuscript [63].

Furthermore, in both clinical and research settings, automated gait analysis systems such as GaitRite® or *ProtoKinetics* Zeno® are widely used [64]. In laboratory settings, instrumented gait analysis using marker-based or markerless motion capture, ground reaction force measurements, and sEMG to assess muscle activity are used in combination with multi-body modeling approaches for in-depth analysis of the biomechanics of human gait on a treadmill or overground [65, 66].

3.2. Balance assessment

Mancini and Horak [55] conducted an extensive methodological review on balance assessments across different age groups. For nursing home settings, the TUG, POMA-B, and FICSIT-4 appear to be feasible and widely-used assessments [67–69].

As mentioned above, the TUG is not only suitable for assessing functional mobility and may indicate the ability of a person to perform ADL, but is also often used to determine fall risk [58]. A recent umbrella review showed that TUG is the most widely used test for fall prediction in older adults, but inconsistent results on fall risk have been reported in the literature [70]. Furthermore, the balance-oriented subtest of the POMA-B is often used to determine balance performance and general risk of falling [71]. Balance is assessed with nine items such as standing up (with/without help) or standing with opened or closed eyes (steady/unsteady). Each item is scored by the examiner with zero to one/two points, and a functional score by summing up all items is calculated. Similar to the TUG, the results for fall risk prediction are not consistent [68]. Another well-known functional balance assessment is the BBS [72]. A meta-analysis revealed heterogeneous findings on the validity of the BBS, i.e. the BBS was only valid for fall prediction in specific subgroups (e.g. individuals younger than 65 years, or individuals achieving between 45 to 49 points) [73]. Finally, the FICSIT-4, which requires an individual to take 7 different stand positions such as the tandem stand and the one-leg stand for 10 s, is suitable and widely used to assess static balance in older adults [74].

Static and dynamic posturography are more valid procedures to determine different aspects of posture [55]. To assess static steady state, for example, individuals are asked to stand on a force plate in different types of stances and their postural sway is determined [75]. For dynamic steady-state balance testing, unperturbed treadmill or overground walking and the movement of the CoM in relation to the base of support are determined [56]. To assess dynamic reactive balance, different tools and approaches such as cable pulling systems, split-belt treadmill acceleration, or an instrumented version of the Posturomed® are used [76–78].

3.3. Muscular strength assessment

Functional lower limb strength assessments in older adults are often done using sit-to-stand movements/chair rise tests. These tests show a large diversity in terms of used equipment (e.g. chair), individual (e.g. age and diseases), and strategy-related determinants [79]. The 5STS and the 30 s chair stand test are widely used in clinical settings. Within the tests, individuals are asked to perform five consecutive sit-to-stand movements in the shortest possible time, or as many sit to stand movements as possible in 30 s. The 5STS is a significant predictor of disabilities with regard to ADL, and a moderate predictor of falls [80]. The 30 s chair stand test shows a moderately high correlation to weight-adjusted leg-press tasks in older adults [81]. For sit-to-stand tests, instrumented versions utilizing motion capturing systems or mobile sensors exist, and may be used to gain deeper insights into motor performance, e.g. they may allow for better distinction between different frailty levels or to detect underlying causes for performance deficits [82, 83]. In clinical settings, handheld dynamometers are often used to determine isometric muscle strength. These tools provide objective and reliable data; however, examiners should undergo training [84]. Furthermore, isokinetic dynamometer machines exist, which allow for measuring the isokinetic strength in laboratory settings through the complete RoM of the tested joints, and due to high resistance, also allow for testing isometric strength [85]. Another advantage over handheld dynamometers is that individuals with limited muscular strength can be tested as the measurement is sensitive even for subtle changes [86].

3.4. Proprioception assessment

In a detailed review, Hillier *et al* [87] provide a comprehensive overview of proprioceptive test procedures. Assessments can be divided into four categories: (1) active and (2) passive joint position detection method, i.e. the individual is provided a joint angle and is asked to reproduce the same angle with the contra-lateral leg after the leg is moved back in a neutral position (active). In the passive condition, the joint is moved; and the individual is asked to indicate when the initially given position is reached. (3) Passive motion detection threshold method, i.e. the joint of the individual is moved, and the individual is asked to indicate when he/she feels the movement. In all three conditions (1)–(3), the degree difference between both positions is measured. (4) Passive motion direction discrimination, which is similar to (3), except that the individual is asked to state in which direction the joint is being moved [87]. The tests can be conducted manually, i.e. the examiner moves the individual's limbs using their own hands and/or measures the results, such as joint angles, with a manual instrument such as a goniometer. Alternatively, the tests can be instrumented or automated, e.g. the individual is moved by an apparatus. To this end, various apparatuses have been used in literature [87].

3.5. Advantages and disadvantages of different human motor performance assessments

To conclude, most motor performance assessments typically conducted in clinical, nursing home and/or care facility settings tend to require less equipment, examiners' skills and/or expertise in tool handling or data analysis than classical laboratory assessments. On the one hand, they are often less time-consuming, and the test-retest reliability is mostly moderate to good. Also, they are well established in different settings and have high practicability. On the other hand, these tests may have lower objectivity, results may vary between examiners, and may show floor and ceiling effects depending on different target groups [55, 118]. Laboratory-based assessments, in contrast, are rather objective, more sensitive to small changes, and may be more suitable to evaluate therapeutic efficiency or determine the underlying causes of motor performance impairments. However, they often require the presence and handling of specific and expensive instruments, highly trained and experienced examiners to operate instruments or administer tools, and can be time-consuming with regard to both administration and data analysis [55, 119]. We anticipate that wearable robotic devices, such as exoskeletons, may (1) extend the capabilities of currently established clinical and laboratory-based assessments, and (2) combine their advantages and strengths, to (3) provide more objective, reliable, and valid human motor performance assessments in the future.

4. Exoskeleton-based motor performance assessment in older adults

Exoskeletons are active or passive robotic devices that fit closely to the body and use rigid or soft structures to assist or augment the user's motion ability [120]. Lower limb exoskeletons can support the whole leg or only one single joint (e.g. ankle or knee). Especially for rehabilitation purposes full leg exoskeletons currently also need crutches to maintain balance. The motor performance of the user while using the exoskeleton has been extensively studied in relation to walking and standing [121]. Current exoskeletons are typically equipped with a variety of sensors (e.g. angle encoders, or IMU) [14]. They monitor the exoskeleton and user's current state to adjust the control system's forces, torques, and paths [122]. Additionally, they use sensor feedback and state estimation to predict the user's movement intention and customize the exoskeleton's movement characteristics [123]. We and others anticipate that in the future, built-in sensors of exoskeletons may also be used for assessing human motor performance [14, 124].

As reported in our recent review on lower limb exoskeletons [14], we postulate three approaches that may be feasible: (1) converting/adapting established, classical test procedures into exoskeleton-based measurements; (2) creating new test procedures and approaches that fit the nature of lower limb exoskeletons to test different motor performance abilities and skills; and (3) analysis of data collected during all-day use of the exoskeleton by a human user to determine how parameters change over time [14, 125]. Almost half of the studies included in our review on lower limb exoskeletons to assess motor performance used fixed stationary treadmill exoskeletons to support the hip and knee; however, for all-day use, mobile exoskeletons are needed. The results of validation studies, especially those focusing on exoskeleton-based proprioception assessment, seem promising and exoskeletons may indeed reduce limitations of traditional proprioception assessments [14]; however, more research is needed and currently available studies have several limitations. In addition, to the best of our knowledge, no study to date has used exoskeletons to measure balance or fall risk [14], albeit exoskeletons to support balance exist [126, 127].

When developing or choosing human motor performance assessments that may be carried out using exoskeletons, many aspects need to be considered, including but not limited to the goal of the assessment (e.g. assessing strength or balance), appropriateness for the target group (e.g. limitations of individuals with regard to motor and/or cognitive status), required resources (e.g. time, space and/or personnel), sensitivity to changes (e.g. sensitivity of the test to capture small changes), and strong psychometric properties (e.g. reliability and validity of the test) [119]. Particularly with regard to exoskeleton-based motor performance tests for older adults, the specific characteristics and needs of this target group must be taken into account, such as decreased muscular strength or proprioception, as well as potentially impaired cognitive function. With regard to the goal of the assessment, it must be considered that outcome variables may differ by setting, i.e. researchers may require different outcomes or test results than clinical professionals.

4.1. Exoskeleton-based gait assessment

Lower limb exoskeletons may be ideally suited for gait analysis due to their design for mobility support and the integration of sensors optimized for gait control. As expected, numerous studies have already used exoskeletons to assess gait phases using different sensor configurations and machine learning methods [128, 129]. The root mean square error between the gait phase estimator and the actual ground truth can vary from 4.10% to 5.53% (within 100% of the gait cycle) [130, 131]. These data could be merged with torque data in assist-as-needed control situations to determine weaknesses in specific joints and muscle groups, but coupled biomechanical human-exoskeleton models only exist for few devices [132]. Exoskeleton data have also been used to determine a walking ability score [133]. To this end, no particular test setup is needed, and data processing could be done while a user is wearing the exoskeleton. For example, Lonini *et al* [134] calculated an exoskeleton-derived walking ability score based on step frequency, standard deviation of the frontal angle, estimated energy expenditure and number of steps in a given time. Similarly, functional mobility tests such a TUG (examplary exoskeleton-based test implementation shown in figure 3), Six-minute walking test or walking speed test (see table 1) can be enhanced using additional information and data from an exoskeleton [134]. For example, exoskeletons may capture spatio-temporal parameters such as speed, or step length. Combining these exoskeleton-assessed parameters with functional mobility tests (e.g. six-minute walking test), could generate new insights regarding underlying medical conditions or training/rehabilitation process. Indeed, one study using a hip exoskeleton showed that a root mean square error of 0.061 m s^{-1} can be achieved during ground level walking in older adults, which may be sufficient valid for motor performance assessment [135]. Since many older adults need mobility support and aids such as crutches and walkers, it is conceivable to provide mobility support with an exoskeleton and, at the same time, control for this support when evaluating exoskeleton-based motor performance tests [133]. However, all exoskeletons have a certain degree of influence on human gait; thus, exoskeleton-based assessment of gait parameters may not necessarily be reflective of gait without wearing an exoskeleton [136].

Table 1. Brief overview of different lower limb motor performance assessments for older adults, evaluation of adaptability for lower limb exoskeleton-based implementation and minimum requirements for such implementation; ✓ fully implementable, (✓) partially implementable; V = controlled for validity; R = controlled for reliability; Adpt = Adaptable for exoskeleton-based implementation.

Test/Assessment	Task	Performance variable	V	R	Adpt.	Minimal requirements regarding recording/ calculation to determine the performance variable
Gait						
Timed Up and Go test (TUG) [58]	Stand up from a chair, walk 3 m, turn around, and sit back down	Time	[58, 68]	[88, 89]	✓	– Start/end of the movement – Time
Walking speed test [90]	Walking between 2.44 m (8 ft) and 25 m	Walking speed	[90, 91]	[90, 91]	✓	– Walked distance – Time
Two-minute/Six-minute walking test [92]	Walking for 2 or 6 min	Walking speed	2 min [93] 6 min [94]	2 min [93] 6 min [94]	✓	– Walked distance – Time
Instrumented gait analysis [66] Optoelectronical system IMU-based system GaitRite®	Walking on a treadmill or overground	(a) Spatio-temporal parameters (e.g. step length) (b) Kinematic parameters (e.g. joint RoM) (c) Kinetic parameters (e.g. peak joint torque) (d) Muscle activity (e.g. sEMG root mean square)	Gold standard[a] e.g. Noraxon System [95] [96]	Gold standard[a] e.g. Noraxon System [95] [97]	✓	(a) – Reference coordinate system – Heel strike/toe off – Time (b) – Exoskeleton joint angles or – Kinematic data and inverse kinematic human model (c) – Kinematic data, – External forces, – Anthropometrics, – Coupled human-exoskeleton model (d) – sEMG

(Continued.)

Table 1. (Continued.)

Balance						
Timed Up and Go test (TUG) [58]	Stand up from a chair, walk 3 m, turn around, and sit back down	Time	[58, 68]	[88, 89]	✓	– Start/end of the movement – Time
Tinetti Performance-Oriented Mobility Assessment (POMA-B) (balance subtest) [71]	Sit, stand up and sit down from a chair, stand (open and closed eyes) and turn	Score (functional balance)	[68]	[68]	(✓)	– Plantar pressure measurement (Postural sway) – Action recognition – Time – Exoskeleton support
Berg-Balance Scale (BBS) [72]	14 different balance tasks (standing, rising, sitting, transferring, reaching)	Score (functional balance)	[68, 98]	[68, 98]	(✓)	– Plantar pressure measurement (Postural sway) – Action recognition – Time – Exoskeleton support
Frailty and Injuries: Cooperative Studies of Intervention Technique (FICSIT-4) [74]	Performing four different stances (feet together, (semi-) tandem, single-leg) for 10 s	Score (functional balance)	[74]	[74]	(✓)	– Plantar pressure measurement (Postural sway) – Action recognition – Time – Exoskeleton support

(Continued.)

Table 1. (Continued.)

Test/Assessment	Task	Performance variable	V	R	Adpt.	Minimal requirements regarding recording/ calculation to determine the performance variable
Force plate based balance assessment [55, 99, 100]	(a) Standing on a force plate (static); (b) Walking on a treadmill (predictive situations/dynamic steady state) (c) Perturbation apparatus (dynamic—reactive)	(a) e.g. postural sway, (b) e.g. margin of stability, (c) e.g. margin of stability,	Gold standard[b]	(a) [101] (b) [102] (c) [103]	(✓)	(a) – Plantar pressure measurement or – Ground reaction force measurement (b) + (c) – Center of mass (anthropometric model) – Leg length – Boundaries of base of support
Lower limb strength						
Five Times Sit-to-Stand test (5STS) [104]	Stand up from a chair, five times in a row	Time	[105]	[106]	✓	– Start/end of the movement – Time
30 s chair stand test [81]	Complete as many sit-to-stand movements in 30 s	Repetitions	[81]	[81]	(✓)	– Start/end of the movement – Time
Handheld dynamometers [107]	Individual is asked to generate maximum force against a dynamometer placed on predefined lower limb landmarks and held by an examiner	Isometric force	[108]	[109]	(✓) [c]	– Exoskeleton joint angle – Exoskeleton joint torque

(Continued.)

Table 1. (Continued.)

Isokinetic dynamometer [110]	Individual exerts maximum effort against the resistance throughout the range of motion with constant velocity (isokinetic) or exerts maximum effort against a fixed resistance without movement of the limb (isometric)	Isokinetic and isometric force (e.g. maximum joint torque, angular position of maximum torque)	e.g. Biodex System [111]	e.g. Biodex System [111]	(✓)[c] (e.g. [112])	– Exoskeleton joint angle – Exoskeleton joint torque
Proprioception						
Active and passive joint position detection [87]	Individual is positioned with a specific joint angle or posture and (1) active: is asked to reproduce this position without visual cues; or (2) passive: the leg is moved through the whole RoM and the individual is asked to stop in the previous given position	Error between the given and reached position (joint angle)	[113]	[113]	✓(e.g. [114])	– Exoskeleton joint angle – joystick or Button to press
Passive motion detection threshold [87]	Examiner moves the joint without active participation. Individual signals as soon as they notice joint movement	Difference between start and responded position (joint angle)	[113]	[113]	✓(e.g. [115])	– Exoskeleton joint angle – Button to press
Passive motion direction discrimination [87]	Examiner moves the joint without active participation. Individual signals as soon as they notice in which direction the joint is moved	Difference between start and responded position (joint angle) and movement direction	[87]	[87]	✓	– Exoskeleton joint angle – Joystick or buttons to press

[a] The instrumented gait analysis with optoelectronical measurement systems combined with forceplates and sEMG is regareded as the gold standard in gait analysis [116].

[b] The instrumented balance assessment conducted on laboratory grad force plates is considered as the gold standard in balance assessment [55, 117].

[c] Only with a fixed frame mounted exoskeleton with rigid structure.

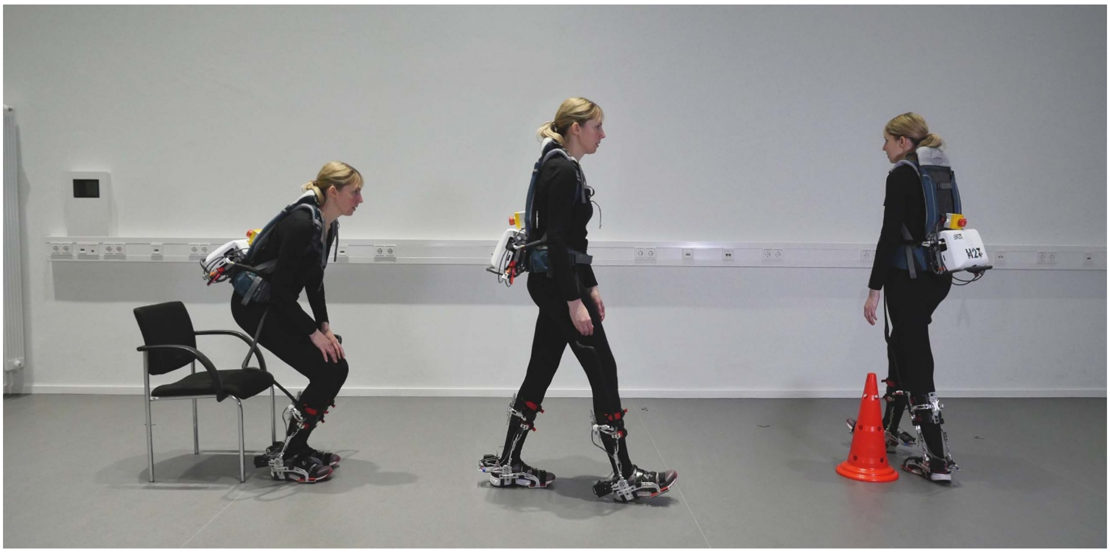


Figure 3. Exemplary realisation of a TUG test using a mobile ankle exoskeleton and its built-in sensors.

4.2. Exoskeleton-based balance assessment

Shirota *et al* [18] provide an overview of robots which can be used for human balance assessment. They report that mobile exoskeletons available to date can only be used for balance tests in the anterior–posterior direction due to their limited DoF. If a more comprehensive balance evaluation is desired, the exoskeleton should match the lower limbs' DoF in humans. For example, ankle exoskeletons often only have one or two DoF [137]. If and when these challenges can be overcome, then we postulate that exoskeleton built-in pressure sensor insoles, interaction (between human and exoskeleton) force sensors, joint angle sensors, and joint torque sensors may be used to determine human balance performance. Furthermore, static and dynamic balance could be tested by using the actuators for inducing perturbations during standing and walking. With regard to classical balance assessments such as BBS or POMA-B, not all aspects (e.g. support of the hands/arms to keep balance) may be controlled for by an exoskeleton, and standardization and clear instructions by the examiner are thus necessary. Furthermore, instrumented versions, using IMU for example, of rather simple tests such as the TUG are already available [59]. Additional sensor data and parameters calculations like sub-phase analysis, postural sway, or margin of stability from an exoskeleton can provide deeper insights into a person's static and dynamic balance performance [59, 138]. In addition, to date, it appears to be easier to use rather simple stance (i.e. tandem, double leg) and movement tasks (e.g. exoskeleton induced perturbations) to assess static and dynamic balance using exoskeletons. However, it must be noted that the weight of an exoskeleton will have an influence on test performance, especially during single leg stance or dynamic balance tests. Thus, correction procedures for such biases must be considered. It is also likely that new balance parameters will need to be developed, depending on the amount of support the user receives from the exoskeleton to maintain balance.

4.3. Exoskeleton-based muscular strength assessment

Studies have used dynamometry-based approaches with stationary exoskeletons fixed to a rigid frame to assess muscular strength [139, 140]. Isokinetic movements with mobile lower limb exoskeletons are only possible to a limited extent, due to missing fixation, and structures may have limited stability in favor of lightweight design. For example, Bolliger *et al* [139] only included women in their study because of structural concerns of the Lokomat (treadmill fixed) exoskeleton. Therefore, exoskeleton-based functional assessments or creation of individual strength scores seem to be more feasible, especially for older adults. Lower limb strength tests, such as 5STS, could be improved for frail older persons in that the exoskeleton could assist in performing the test. During rehabilitation or training, even the smallest changes could be detected when less or more support is required. To the best of our knowledge, this has not yet been reported in the literature. Furthermore, the use of additional sensors, such as pressure soles, could improve the validity of exoskeleton-based muscular strength tests, and reduce the influence of other variables such as balance or mobility [141]. Regarding the creation of a strength score, only one study [142] calculated an individual hip strength index derived from the exoskeleton, and based on the interaction torque between the user and the exoskeleton, and the tracking of the position of the limbs. Such approaches thus seem to be promising on an assist-as-needed basis, and for deriving individualized training recommendations.

4.4. Exoskeleton-based proprioception assessment

Assessment of proprioception, from a technical, hardware design-centered perspective, needs an accurate measurement and control of the joint angles and velocities, albeit individuals need to give feedback to the examiner or software system during proprioception assessments. We hypothesize that tasks such as 'passive motion detection threshold' or 'joint position detection' may be possible to be carried out with exoskeletons, and first studies using the treadmill fixed 'Lokomat' exoskeleton to this end have been published [114, 115]. They report a good to excellent test-retest reliability within the exoskeleton-based assessments with intraclass correlations ranging between 0.88 and 0.96 depending on participant status and tested joint (knee, hip) [115]. In addition, dynamic approaches to assess proprioception may also be possible by using exoskeletons, and studies have examined perturbations induced by an ankle exoskeleton during treadmill walking [143]. Of note, exoskeleton-based proprioception assessment may be limited by the interfaces between the human body and the exoskeleton, as these could give cutaneous and acoustic feedback, thus potentially biasing the assessment [115].

4.5. Conclusion on exoskeleton-based assessment

We conclude that the assessment of human motor performance using exoskeletons may be feasible in the future with some exceptions, and could have several advantages over established assessments currently used in clinical and/or laboratory settings. Exoskeleton-based human motor performance assessment may be suitable even for individuals with motor disabilities, who are often unable to participate in traditional motor performance assessment. Furthermore, if and when developed and validated, exoskeleton-based measurements may be performed throughout the day without a pre-defined test procedure or limited assessment time. In terms of enhancing classical functional motor performance assessment, exoskeleton data can be used to divide functional tests into different sub-phases that can be analyzed separately. Furthermore, additional parameters such as gait phase duration, side differences or classical laboratory parameters such as postural sway may provide new insights into the performance of older adults. Such continuously collected motor performance data could be used to identify trends and even subtle changes in specific motor performance parameters over time, and could inform individualized training to counteract motor performance impairments as early as possible. This may be particularly valuable and critical for older adults or individuals with impairments or disabilities. Furthermore, the exoskeleton control mechanisms itself may be optimized by using human motor performance data, e.g. by self-adapting trajectories and the amount of needed support. For training purposes, the exoskeleton could adapt in real time to the current motor performance status of the user, and provide movement related feedback, which can be critical for balance and gait training, amongst others [133, 144].

5. Recommendations for lower limb exoskeleton development to assess motor performance

Designing exoskeletons to meet all motor performance assessment requirements as mentioned above is challenging and potentially impossible. Thus, compromises are necessary based on the specific task's requirements. This section explores key exoskeleton design and development requirements for various motor performance assessments.

One of the main challenges in exoskeleton-based motor performance assessment is to limit or potentially avoid bias, which may be due to the limitations of exoskeletons itself, or the impact that an exoskeleton has on motor performance, e.g. when providing support. Exoskeleton devices are complex mechatronic devices and often feature limitations resulting from simplified mechanics aimed to lower exoskeleton mechanical complexity. Limitation examples include but are not limited to oversimplified joints, reduced exoskeleton DoF, or exoskeleton kinematics that restrict the user's RoM. Furthermore, distortions arise from the negative effects of additional mass and inertia introduced by the exoskeleton device attached to the user's limbs.

Full RoM of the exoskeleton joints is an important technical requirement for the exoskeleton to be used in motor performance assessment. It is crucial for exoskeletons to allow user motion without counter forces or misalignment, even at the device's movement limits. If the exoskeleton RoM is lower than the user's RoM, then the user's RoM cannot be determined.

Limited exoskeleton RoM or DoF also affects the individual's natural balance recovery strategy and may hinder the successful execution of human motor performance assessment, especially related to balance and gait. Consequently, altered human compensation strategies would bias any measurement by affecting both balance [18] and individual muscle activity [145]. For safety purpose, e.g. to avoid straining an individual's joint beyond physiological limits, exoskeletons should also feature adjustable mechanical and software measures to safely operate within an individual's RoM. This can be done, for example, through adjustable mechanical hard stops and adaptable software limits for joint angles and torques.

However, fully addressing kinematic compatibility issues with mechanical means can result in bulky exoskeleton devices, and (excessive) mass at positions far away from a user's CoM. Distal mass increases the inertia of a user's limbs and has a significant impact on motor performance. Furthermore, the lightweight aspect of exoskeletons is important because the added mass negatively affects motor performance tasks energetically [146]. Research has shown that compensating for changes related to exoskeleton mass and changes in inertia cannot be fully compensated for by control methods alone [147]. We hypothesize that this could be reduced by (1) keeping the exoskeleton mass and inertia as low as possible, (2) compensating with control methods, and (3) observing task parameters that are less affected by exoskeletons mass. For example, Jin *et al* [147] show that weight compensation in exoskeleton control alone partially counteracts the influence of the exoskeleton on certain gait parameters, such as step height and knee flexion, but not, for example, step length.

With regard to exoskeleton type and design, two types of exoskeleton devices, namely soft exosuits and rigid exoskeletons, are used in current research [14, 148]. Both types feature different advantages and disadvantages when considering their suitability for human motor performance assessment.

Soft exosuits rely on fabrics and textiles to transmit forces, resulting in a good kinematic compatibility and comfort through easy alignment and adaptability [149]. Although they are more light weight, their lack of rigid support structures means they provide less assistance. In addition, these assistance forces cannot be transferred as accurately as in rigid exoskeletons, and joint angles may not be directly determined using traditional angular encoders.

Rigid exoskeletons, on the other hand, are robust enough to support optimal assistance torques [150], but their structure requires complex designs to retain these advantages while minimizing the impact on a user's kinematic. Furthermore, the rigid structure supports the exoskeleton itself by transferring its weight to the ground, thereby limiting the weight load on the user [151].

To ensure a good kinematic compatibility between the user and the rigid exoskeleton, micro[4]- and macro[5]-misalignments need to be minimized. Oversimplified exoskeleton joints and incorrect exoskeleton positioning on the human body, may result in a kinematic mismatch between the anatomical joint and the exoskeleton [153], and lead to parasitic forces [154] and increased pressure and shear at fixation points [155]. The micro-misalignments require novel joint mechanism designs to better mimic the motion of anatomical joints [156]. The macro-misalignments can be avoided or minimized with a certain amount of adjustable elements and customizable fits ensuring a well-fitting, personalizable structure to accommodate, for example, for different leg segment lengths across users. Therefore, the rigid passive structures of an exoskeleton, such as the cuffs or joints, must be adjustable in length and width. Anthropometric exoskeleton design, i.e. designs close to human dimensions, has been shown to be optimal for assessing human motor performance, based on results from previous studies [14].

As shown in table 1, the precise measurement of the joint angle is a key feature for the assessment of motor performance in all categories. The use of an anthropometric rather than non-anthropometric exoskeleton design eases and potentially improves validity of joint angle measurement. For rigid exoskeletons, human joint angles can be directly estimated from exoskeleton joint angles using angular encoders, or hall-effect-based sensors directly embedded in exoskeleton joints. Such angle estimates are precise with a root mean square error between 0.135° (ankle) and 7.2° (hip) [157, 158] for some, but not all, use cases (e.g. inverse dynamic calculations). In contrast, soft exosuits often rely on IMU-based angle estimation or may require novel type of sensor systems, as there are no clear attachment points and levers [159]. The angular accuracy of the exoskeleton depends on the speed of movement, the support, and the angular position. Deviations can occur due to the soft, adaptable material connecting the exoskeleton and human [157, 158].

As noted in table 1, particularly motor performance tasks conducted in field settings may require some kind of action and posture recognition to determine the start and end of a movement, and to determine if the tasks were carried out correctly. Therefore, different types of sensors (e.g. encoder or IMU) have been proposed in the literature, and the data is typically analyzed with rule-based or pattern recognition (machine learning) classifiers [160].

For some functional tests, it is also crucial whether a person performs a test such as the POMA-B with or without external support, i.e. with an examiner or the exoskeleton. For the latter, joint torque sensors and controllers can measure the support provided by the exoskeleton. It is also important to assess if the

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[4] misalignments caused by the intricate nature of the musculoskeletal system, resulting in misaligned joint rotation axes between the exoskeleton and the user during movement [152].

[5] misalignments caused by different DoF between human and exoskeleton [152].

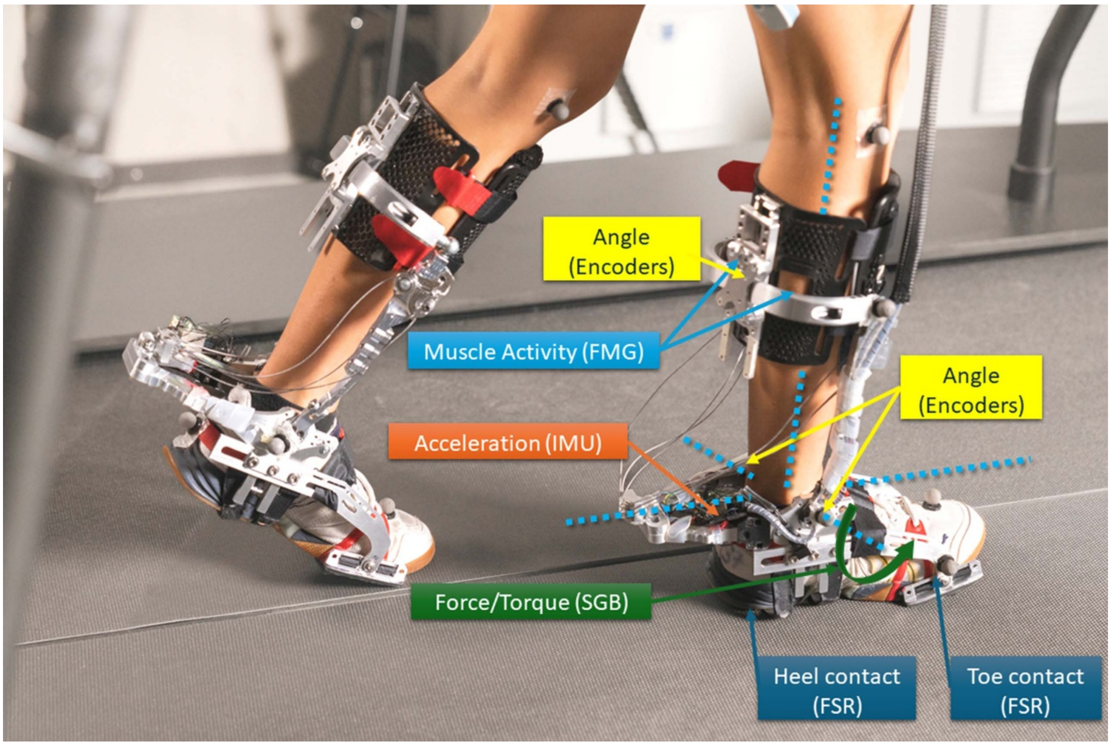

Figure 4. Exemplary sensor setup for an ankle exoskeleton to assess human motor performance. The arrows indicate the potential placement of the sensors, except for the joint torque arrow which indicates the estimated ankle joint torque in plantar and dorsiflexion. FMG = force myography; IMU = inertial measurement unit; SGB = strain gauge bridge; FSR = force sensing resistor.

measured power is for support only, or due to user resistance. Techniques like sEMG or FMG (will be discussed below) could be useful for this.

Finally, accurate measurement of time is critical for exoskeleton-based motor performance assessment. Although time measurement is rather simple, it is necessary that the exoskeleton has a response rate that exceeds the speed of human physiological responses [161]. An exoskeleton with a slower response rate than a human would negatively impact the normal human physiological responses. For example, the recommended sampling frequency for static testing in human postural control should lie between 100 to 1.000 Hz [162], and lower frequencies may impair the quality of measured signals.

5.1. Requirements for gait assessment

Spatio-temporal parameters can be derived from integrated joint angle sensors (encoders) combined with pressure insoles for heel strike detection, IMU [163], and measurement/estimation of GRF with pressure insoles [164]. An exemplary sensor setup for ankle exoskeletons to assess human motor performance is provided in figure 4. When calculating stride length, the walked distance can also be determined, which is important for several functional walking tests such as the Six-minute or Ten-meter walking tests. The latter could provide additional information about postural sway, thereby replacing motor performance assessments carried out on force plates [165, 166]. Combining the information provided by these sensors may contribute to the assessment of gait speed, phases, and asymmetry during different walking tests, but is also also dependent on step control and the interface of the exoskeleton [167, 168].

Combining joint angle information with external forces, as described below, and a coupled human-exoskeleton model would allow calculating net human joint torques [169]. However, as mentioned above, these models are still rare and very challenging to develop [132, 170], and also require a precise measurement of all necessary components [132, 171].

Muscle activity is often measured using surface sEMG, and is currently used for control purposes in exoskeletons and for motion analysis in biomechanics, as well as for strength assessment. The use of sEMG electrodes while wearing an exoskeleton requires significant preparation and experience, as the quality of the sEMG electrode signal is affected by misplacement, skin condition, and the quality of skin contact [172]. The interaction of clothing or cuffs placed over the electrodes may result in movement or detachment of the electrodes, thereby preventing reliable measurement. This requirement with regard to the accurate placement of sEMG electrodes limits the possibilities of the use of these electrodes for exoskeleton-based motor performance assessment to mainly controlled laboratory settings. To this end, wireless sensors may be a more feasible solution [173]. Preferably, sensor systems for measuring or estimating muscle activity could already be integrated into the exoskeleton cuffs.

FMG methods demonstrate an alternative means of acquiring information about muscle activity by assessing mechanical activity of muscles during contraction. Compared to sEMG, FMG-based signal processing is less vulnerable to the quality of skin contact and, depending on the type of sensor, may require less signal filtering and post-processing. Indeed, FMG was shown to be effective in daily motion detection [174] and joint angles estimation in the lower extremities [175]. These mechanical effects can be detected regardless of clothing, and would therefore allow the integration of such systems into the exoskeleton cuffs. FMG based methods have also been used for motion classification, intention recognition, gait event detection, and estimation of knee joint angle [175–178], and thus may also be used to evaluate muscle activity during exoskeleton-based gait performance assessments.

5.2. Requirements for balance assessment

It should be noted that insole pressure sensors, which could serve as portable force plates, differ in accuracy from their laboratory counterparts [164] and should be used with caution. The use of sensorized insoles requires specific shoes or a standardized preparation involving good positioning of the soles in the shoe. However, research shows that kinematic measures, internal joint loads and GRF can be estimated using IMU-based wearable sensors alone [179–181], and thus balance-related parameters such as postural sway could be calculated.

Several wearable sensors such as IMUs and related methods have been proposed to detect and assess the risk of falls, especially in older individuals [182, 183]. The information provided by IMUs can thus be beneficial not only for fall detection but also during functional balance tasks such as the TUG test [184]. Different methods based on IMU to assess balance in older adults have already been described [185]. The IMUs can detect variances in postural sway based on vertical and horizontal deviations of CoM [186, 187] or estimate the position of CoM with respect to the the base of support [188].

To date, dynamic reactive performance assessments are mainly performed using a perturbation apparatus and aim to calculate the margin of stability or whole-body angular momentum, among others [78, 189]. Incorporating these assessments into the exoskeleton would require the use of back-drivable actuators that can also induce joint torques in the opposite directions of movement [190]. Alternatively, additional actuators such as gyroscopic actuators, and perturbation mechanisms would need to be integrated into the exoskeleton to induce specific perturbations during use [191].

5.3. Requirements for muscular strength assessment

Some of the requirements, as outlined in table 1, for evaluating sit to stand movements, such as action recognition, are already discussed in the preceding subsections.

Dynamometers are often used to assess lower limb strength under isometric and isokinetic conditions. For an exoskeleton-based assessment, this would require the integration of joint torque sensors and the ability to switch between position and torque control depending on the application. Although the use of dynamometers to estimate the joint torque is common, these measurements are not exactly comparable to internal joint torques [192]. Internal joint measurements require additional sensor information, i.e. kinematics and kinetics, and the aforementioned coupled human-exoskeleton model to accurately estimate internal joint torques. In addition, pressure plates or sensorized insoles can measure the vertical ground reaction forces under the user's feet and thereby provide further information.

In strength assessment, muscular activity, as mentioned above, can be used to determine the force itself; however, this is still very challenging and is currently best addressed by different machine learning approaches [193, 194]. Also, muscle activity is used more frequently to determine muscle fatique and muscle contraction intensity [195, 196].

5.4. Requirements for proprioception assessment

An exoskeleton-based proprioception assessment would need to fulfill several requirements. For example, the exoskeleton should serve both as a measurement and an input device. Both the accuracy, repeatability and the proper placement of joint angle sensors on the exoskeleton are important, as misaligned sensors can lead to incorrect data, affecting the assessment's reliability. These requirements are met using a well-fitted exoskeleton, i.e. kinematically compatible exoskeleton, that mimics the natural movement of the human body can enhance the accuracy of proprioception measurements.

In this case, potential macro- or micro-misalignment induces additional sensations on the user and cutaneous feedback. Cutaneous feedback is caused by excessive pressure or friction on the skin and can interfere with proprioceptive feedback signals. Reducing noise, especially mechanical noise from the exoskeleton, is crucial in order to avoid influence on the user's perception.

The zero-torque or transparent mode, which provides no resistance during joint rotation, is essential for accurate proprioception assessment without external influences. Accurate and well-placed torque sensors simplify the implementation of this mode by measuring and compensating for nonlinearities in actuation not captured in mathematical models [197].

5.5. User and examiner perspective

An output device such as a mobile application, or augmented reality glasses that guides the user and/or the examiner during an exoskeleton-based motor performance assessment in a simple yet effective way would be highly desirable. To minimize bias, structured familiarization or certain degree of embodiment is highly recommended [14, 198]. Usability may be enhanced, if necessary, through a simple, standardized procedure for sensor calibration.

Finally, safety [121], privacy [199] and certification [200] are further issues that need to be addressed before exoskeletons can be used to assess motor performance.

6. Conclusion

We postulate that various motor performance assessments that are routinely performed in clinical or nursing home/care facility settings, could be carried out using an exoskeleton in the future. While adaptations may be needed or specific, novel exoskeletons may need to be developed depending on the motor task to be performed, integrating wearable robotics such as exoskeletons into healthcare for assessment purpose may be a likely and realistic scenario in the future. To ensure reliability and validity of exoskeleton-based motor performance assessments in humans, the exoskeletons must fulfill several technical requirements, and various design and control-related challenges will need to be overcome. As exoskeletons will become more widely-available in the medium- and long-term, we anticipate that they will also be a promising tool for assessment and monitoring of motor performance. Ultimately, exoskeleton-based motor performance assessment and monitoring may contribute to maintain or improve independence and quality of life among older adults.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Ethics approval and consent to participate

Not applicable

Conflict of interest

The authors declare that they have no competing interests.

Consent for publication

All authors declare their consent for publication.

Authors' contributions

T M, A W, T S and J K R were responsible for the conceptualisation of the manuscript. T M, M D, C M and J K R prepared the first draft. All authors were involved in writing, reviewing and editing the manuscript. All authors read and approved the final manuscript.

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ORCID iDs

Tobias Moeller https://orcid.org/0000-0003-0454-4833
Melina Beyerlein https://orcid.org/0009-0000-9974-5368
Michael Herzog https://orcid.org/0000-0003-1363-8372
Bettina Barisch-Fritz https://orcid.org/0000-0003-4801-2310
Charlotte Marquardt https://orcid.org/0000-0002-5757-1512
Miha Dežman https://orcid.org/0000-0001-7160-749X
Katja Mombaur https://orcid.org/0000-0003-1353-0943
Tamim Asfour https://orcid.org/0000-0003-4879-7680
Alexander Woll https://orcid.org/0000-0002-5736-2980
Thorsten Stein https://orcid.org/0000-0002-7885-7085
Janina Krell-Roesch https://orcid.org/0000-0003-4011-9842

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