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Compensation due to age-related decline in sit-to-stand and sit-to-walk

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A R T I C L E   I N F O

A B S T R A C T

Capacity is the physiological ability of the neuromusculoskeletal systems; this declines with age. This decline in capacity may result in the inability to stand up (sit-to-stand, sit-to-walk), which is an important movement for independent living. Compensation, as a result of functional redundancy, is key in understanding how much age-related decline can be tolerated before movement limitations arise. Yet, this topic has been underexposed in the biomechanics literature. The purpose of this systematic review was to approach the literature on sit-to-stand and sit-to-walk studies from the perspective of compensation and create an overview of our current understanding of compensation in standing up, identifying the limitations and providing future recommendations. A literature search was performed, using the keywords and their synonyms: strateg*(approach, technique, way) AND, sit-to-walk OR sit-to-stand OR rise (raise, arise, stand, stand-up) AND chair (seat). Inclusion criteria: full articles on biomechanics or motor control on sit-to-stand or sit-to-walk in healthy adults (<60y), healthy or frail elderly adults (>60y), and adults with osteoarthritis. The results show that the experimental set-ups and musculoskeletal models in STS and STW studies generally exclude compensation by using restricted protocols and simplifications. Moreover, factors are mostly analysed in isolation, excluding confounding causes within capacity and/or movement objectives which limits the generalization of the results. Future studies in the standing up task should consider to (1) determine the effect of varying arm push-off strategies, (2) focus on sit-to-walk, (3) determine the biomechanical implications of asymmetry, and (4) incorporate assessments of physical capacity as well as changes in psychological priorities.

Contents

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Glossary

Capacity: The physiological abilities of the neuromusculoskeletal system. With this definition of capacity, we do not directly account for changes in the endocrine, immune, cardiovascular, respiratory, renal, or brain systems.

Compensation: An alteration in movement strategy in relation to a baseline (e.g., previous state or a control group). Compensation originates from the redundancy in the muscle architecture of the human body (functional redundancy). Humans compensate by altering their movement trajectory and/or altering the muscle recruitment to complete a task.

Compensation for capacity: An altered recruitment of neuromusculoskeletal resources in response to a low reserve (relatively high task demand) in any part (neural, muscular, skeletal) of the neuromusculoskeletal (NMSK) capacity that can occur at any moment during task execution.

Compensation for movement objectives: Altered movement strategies due to changes in the weighting of movement objectives.

Frail(ty): Frailty is characterized by a state of vulnerability to medical stressors.

Movement objectives: The applied motion strategy of humans is probably a consideration of metabolic energy, velocity, stability (safety), and/or pain avoidance, which we refer to as the movement objectives. Note that the specific objectives that are optimised in daily movements are not yet known.

Movement strategy: Motion trajectory and muscle activations executed to fulfil a movement task.

Muscular capacity: The physiological abilities of the muscular system.

Neural capacity: The physiological abilities of the (peripheral) nervous system and the sensory feedback system, which are divided into the visual, auditory, vestibular systems, and proprioception.

Reserve: task specific difference between the capacity and the task demands. As task demands vary over the duration of the task, so does reserve.

Sit-to-stand (STS): Task in which a human stands up

Sit-to-walk (STW): Task in which a human stands up and walks. STW requires merging of a discrete task (standing up from a chair) with a rhythmic task (walking) and these two tasks overlap near the instant of seat-off.

Skeletal capacity: The physiological abilities of the skeletal system.

Standing up: Movement in which human rises from a chair. This can either be STS or STW.

1. Introduction

Prolonging independence for older adults is a major concern for our ageing societies (UN 2019). One of the more important movements in daily life is standing up, for example, getting up from a chair, getting out of bed, or leaving the toilet. When this can no longer be performed independently, then in-home care or moving to a care facility is required. Its importance is highlighted by the inclusion of the timed-up-and-go test (TUG), which times patients while standing up from a chair, walking 6 m, and sitting back on the chair, when quantifying frailty as part of a validated scale (Rolfson et al. 2006). The mechanisms that contribute to mobility impairments in standing up are complex, overlapping, and interdependent.

Age-related mobility impairments do not promptly arise at the onset of physical decline due to redundancy. Redundancy is both biological redundancy, referring to the physiological reserve, and functional redundancy, referring to the redundancy in the muscle architecture of the human body. The result of functional redundancy is defined as *compensation* (Kruk et al. 2021). Compensation can be a variation in the planned *movement trajectory* described by kinematics, for example standing up from a chair using the armrests. Compensation can also be altered *muscle recruitment*. A possible need of altered recruitment in healthy ageing could be the relative difference in decline of muscle strength between muscle groups. Compensation is generally underexposed in the literature.

Compensation can occur for two reasons. *Compensation for capacity* is the result of a lack of neuromusculoskeletal reserve.

Reserve is here defined as the difference between the capacity (the physiological abilities of the neuromusculoskeletal system) and the task demand. *Compensation for movement objectives* is a result of a shift in the relative weighting of movement objectives, reflecting changing priorities, such as an increased fear of falling. Movement objectives are, for example, metabolic energy, velocity, stability (safety), and/or pain avoidance. Within the redundancy of capacity and reserve, the applied movement strategy of humans is probably a consideration of these objectives.

From the onset of physical decline until the moment that movement impairments arise, human movement strategies will include compensation. Compensation is therefore an early indicator of physical decline and as such of importance clinically. Moreover, insight into the interrelationship between compensation and age-related decline in capacity would support clinicians in their rehabilitation practice, as compensation that is beneficial in the short-term may become detrimental for the capacity in the long-term (e.g., joint degeneration).

Compensation as a result of functional redundancy hasn't been studied as such. The purpose of this systematic review is to approach the literature on sit-to-stand and sit-to-walk studies from the compensation perspective and create an overview of our current understanding of compensation in standing up, identifying the limitations of the current state of knowledge, and providing recommendations to address these limitations.

2. Methods

A literature search was performed in the search engine Scopus, using the following keywords (and their <u>synonyms</u>): *strateg* (approach, technique, way)* AND, *sit-to-walk,* OR *sit-to-stand,* OR *rise (raise, arise, stand, stand-up)* AND *chair (seat)* (1st February 2021). Inclusion criteria were: full articles focussed on the biomechanics
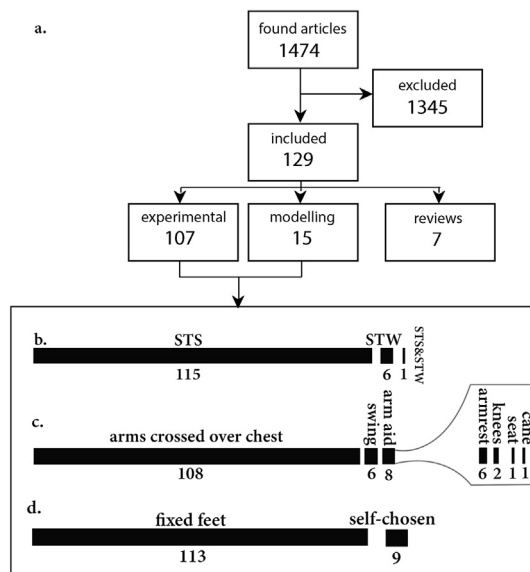
Fig. 1. Number of articles identified to investigate compensation due to age-related decline in sit-to-stand and sit-to-walk categorized by a) study type, b) movement, c) arm restrictions and the kind of arm aid used in the studies. One study could use several arm aid positions. d) initial foot placement.

and motor control on sit-to-stand (STS) or sit-to-walk (STW) in healthy adults (<60y) and healthy or frail elderly adults (>60y). Non-English articles were excluded. Although the review was targeted at healthy ageing, adults with osteoarthritis were also included, as this pathology is highly prevalent in older adults (over 50% of adults over 65-year of age (Cheng et al. 2010)) and research on this topic is extensive. The reference lists were reviewed for any missing articles from the database search. 1474 articles were found, of which 129 fulfilled the inclusion criteria. These comprised 107 experimental, 7 review, and 15 modelling papers (Fig. 1).

The articles were then analysed by first identifying if and how **compensation (step 1)** was considered in the experimental set-up. Then capacity measures (e.g. strength measures) and/or possible psychological reasons (e.g. fear of falling questionnaire) for

compensation that were considered were determined. Articles were then categorized into **Compensation for Capacity (step 2)**, divided into neural, muscular, and skeletal capacity, and/or **Compensation for Movement Objectives (step 3)** in which we considered energy, speed, pain, and safety. With the structured knowledge on healthy age-related declining variables in capacity (Kruk et al. 2021), knowledge gaps on age-related compensation strategies in standing up were identified to enable recommendations for future research to be made.

3. STEP 1: Compensation strategies

First we identified the compensation that was considered in literature, where compensation is defined as movement alterations to
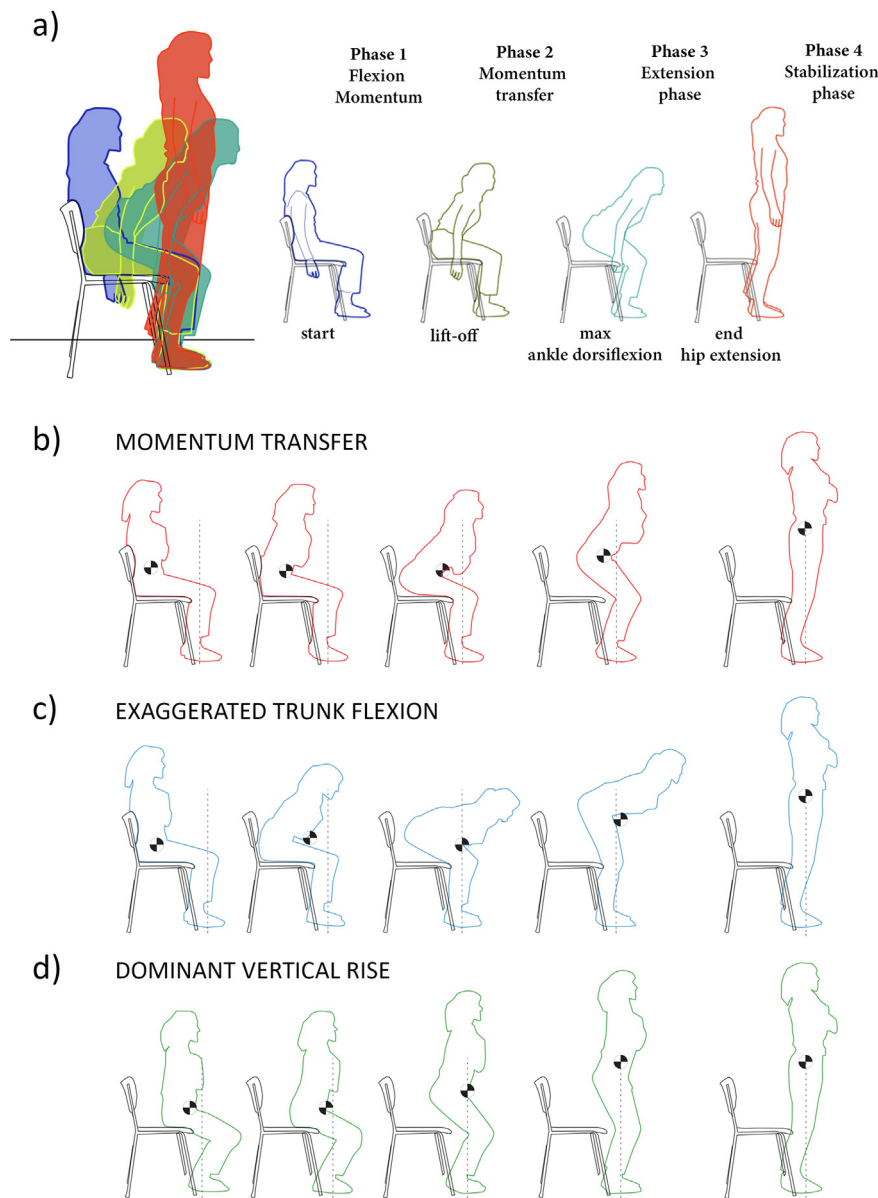
Fig. 2. a) The common way to describe standing-up in four phases (Hughes and Schenkman 1996). Phase 1 - flexion-momentum phase: begins with initiation of the movement and ends just before the buttocks leave the chair (lift-off); note that prior to this visible onset of the STS movement, anticipatory actions can be noted (Frykberg et al. 2012; Boukadida et al. 2015). The head-arms-trunk segments are the main contributors to the body's forward propulsion prior to lift-off during STS. Phase 2 - momentum-transfer phase: begins as the buttocks are lifted from the seat of the chair and ends when maximum ankle dorsiflexion is achieved. Phase 3 - extension phase: initiates just after maximal ankle dorsiflexion and is completed when the hip first ceases to extend. Phase 4 - stabilization phase: begins just after the hip-extension velocity reaches 0°/sec and continues until all motion associated with stabilization from rising is completed. In the STW motion, Phase 4 starts when the heel of the swing leg leaves the ground and ends with the next contact between the heel and the floor (Dehail et al. 2007). A recent article proposes a density-based clustering method for a normative description of the STS events (Norman-Gerum and McPhee 2020) b) Momentum Transfer (MT), c) Exaggerated Trunk Flexion (ETF), d) Dominant Vertical Rise (DVR).

compensate for a lack of capacity or a change in weighting of movement objectives in relation to a baseline, for example compared to a previous state or a control group. The age-related compensation identified in literature for standing up include: trunk movements, arm movements, pacing (related to a stop in between standing and walking), and asymmetry. Most studies typically used standardized experimental protocols, restricting aspects of compensation. This is the result of the trade-off between replication of daily practice to allow for clinical translation and standardization of the protocol to improve repeatability, robustness, and comparability.

3.1. Arm and trunk strategies

Only eight out of the 129 studies allowed the use of arms (push-off) in the experimental protocol. When arm movement was restricted, STS strategies were described by four variables: trunk flexion, velocity of the centre of mass (COM), and the distance between the COM and the base of support (BOS). With these variables, three observed strategies were found: momentum transfer (MT), exaggerated trunk flexion (ETF), and dominant vertical rise (DVR) (Fig. 2).

The MT strategy is characterised by upper-body flexion at lift-off and continuing through the initiation of knee extension, with a smooth transition to simultaneous back and knee extension (Scarborough et al. 2007). Hughes and Schenkman (1996) and Scarborough et al. (2007) found that this strategy was used by 50% (11/22) and 68% (65/95) of their participants, respectively (Table 1).

The ETF strategy is described as an exaggerated trunk flexion prior to lift-off, frequently followed by further trunk flexion that places the COM over the BOS during lift-off and results in delayed trunk extension during the final transition to erect posture (Scarborough, McGibbon, and Krebs 2007). This strategy uses little horizontal momentum, relying mostly on the knee musculature to extend the knee. This group used several other preparatory movements to position themselves for rising; generally, participants moved the buttocks forward and feet backward, moved the trunk slowly forward and then extending to the standing position. The peak horizontal accelerations of the COM for the ETF strategy are less than half of the MT strategy (Shia et al. 2018). ETF was used by 18% (4/22) and 17% (16/95) of the participants in the studies of Hughes and Schenkman and Scarborough et al., respectively (Table 1).

The dominant vertical rise (DVR) strategy shows a stagnation of forward trunk flexion immediately at lift-off, followed by dominant vertical COM displacement and knee-hip extension, with trunk extension movement delayed until after knee-hip extension is complete (Scarborough et al. 2007). Scarborough et al. reports that 15% (14/95) of their participants used this strategy. The strategy was not described by Hughes and Schenkman (1996) as they only described the 'combined category group' with participants who did not fall in the MT or ETF category (32% of the participants; 7/22; Table 1). This combined category group reduced the COM to BOS distance prior to lift-off, but still required momentum to achieve the standing position.

Studies with unrestricted arm movements have mostly been observational studies focussing on two key points: the *necessity* of using arms (mostly related to Compensation for Capacity), and the *preference* of using arms (mostly related to Compensation for Movement Objectives). Arms can be used to push-off on an armrest, seat, knee, or walking aid or can be swung to generate momentum. With a seat at knee height almost half of a group of healthy elderly (48%) were unable to stand up without the use of arms (Mazzà et al. 2004). In a study on osteoarthritis (OA) patients, more than 80% of the participants were unable to stand-up without

Table 1
Overview of studies categorizing STS and STW strategies while standing up from a chair.

Ref.	Seat height (% refers to knee height)	Task	Number of participants	Age (years)	No arms	MT	ETF	DVR	Co.	Arm swing	Push off arms	AC	AK	AR	Unable to rise
Hughes and Schenkman (1996)	six heights: 43.2–55 cm	STS	22	72 (65–105)	100%	50%	18%	–	32%	–	–	–	–	–	–
Scarborough et al. (2007)	100%	STS	95	MT: 75.34 ± 7.32 ETF: 74.02 ± 6.66 DVR: 75.59 ± 5.62	100%	68%	17%	15%	–	–	–	–	–	–	–
Mazzà et al. (2004)	80%	STS	131	78.1 ± 8	41%	..	..	..	..	13%	13%	..	..	..	33%
	100%	STS	131	78.1 ± 8	52%	..	..	..	..	8%	18%	..	..	..	22%
	120%	STS	131	78.1 ± 8	58%	..	..	..	..	12%	27%	..	..	..	3%
Komaris et al. (2018)	100%*	STW	10	46 ± 7.4	40%	..	..	..	..	50%	70%	20%	60%	–	–
	100%*	STW	12	OA:70 ± 5.3	17%	..	..	..	..	58%	83%	42%	50%	–	–
Dolecka et al. (2015)***	46 cm	STS	10	79.5 (69–90)	20%	..	..	..	..	..	80%	–	37%	43%	–
	46 cm**	STS	10	79.5 (69–90)	23%						77%		40%	37%	

Shown are the percentages of participants that used a specific strategy. In Hughes and Schenkman and Scarborough et al. the use of arms was restricted (arms were crossed over chest). In Mazza et al. the participants were asked to perform a sit-to-stand task, without arms, if unable to rise then swinging arms was allowed, if still unable to rise participants could push using their arms (on thighs or seat). In Komaris et al. an armless seat was used, and there were no restrictions on the use of arms. Their participants performed several trials, noted is the percentage of participants that used a certain strategy in any of these trials. MT = Momentum Transfer, ETF = Exaggerated Trunk Flexion, DVR = Dominant Vertical Rise, Co. = Combined; AC = Arms on seat of chair push-off; AK = Arms through knee push-off; AR = armrest.

– this strategy was not allowed in the experiment.

.. strategy was not further specified.

* Participants performed one to five trials (dependent on their capabilities). If a participant was unable to rise to a standing position, the chair was re-adjusted to 115% of knee height.

** table in front.

*** percentage of trials not participants. Each participant performed three trials.

the use of arms (Davidson et al. 2013). In repetitive trials looking into preferred strategies in standing up, healthy adults change their strategies throughout the trials and frequently used their arms of which 20% pushed off on the chair, 60% pushed off on the knees, and 50% used an arm swing in one or more trials (Dolecka et al. 2015; Komaris et al. 2018) (Table 1). In OA patients, 83% used an arm push-off in one or more trials (50% of the OA patients used a knee push-off and 42% used a chair push off in one or more trials (Komaris et al. 2018)).

Only 8/ 120 studies allowed the use of arms (push-off), which poorly reflects the actual prevalence of applied strategies in daily life, and excludes part of compensation (Table 2). Unrestricted arms in experimental protocols would better reflect daily-life activity, and therefore better translate to clinical practice.

3.2. Assumed symmetry

The second main compensation strategy identified in the literature is asymmetry. With biomechanical asymmetry we refer to asymmetric movement or force applied by contralateral limbs in any of the three movement planes. In the reviewed studies, bilateral symmetry was often assumed (and constrained) by restricting arm movements and analysing a single plane, usually the sagittal-plane, while standing up is task with all planes (Gilleard et al. 2008). Foot positioning of the participants was mostly (113/129 articles) fixed in a symmetrical position (Fig. 1), shoulder width apart, with the knee angle at 90° and foot movement during the trial was restricted. A fixed position of the feet at 90° knee angle influences the COM velocity at seat off (Janssen et al. 2002). Anterior foot placement requires high velocities at seat off, directly followed by a backward deceleration, whereas in posterior foot placement close to the centre of mass, such large velocities are unstable (Shia et al. 2018; Kawagoe et al. 2000; Khemlani et al. 1999). The sequence of movement also differs with foot placement; with an anterior placement the trunk extends first followed by the hip joint and then the knee joint, whereas posterior placement results in a pattern in which the knee joint extends first, followed by the trunk and the hip joint (Kawagoe et al. 2000; Khemlani et al. 1999). In addition, muscle recruitment varies with foot position (Kawagoe et al. 2000; Khemlani et al. 1999).

Significant bilateral asymmetry in healthy participants in movement (feet, arms, trunk), reaction force (feet and arms), and muscle activations during standing up have been reported (Boukadida et al. 2015; Lundin et al. 1999; Caruthers et al. 2016; Dolecka et al. 2015; Gilleard et al. 2008). The initial position of the participants is critical in evaluating biomechanical asymmetry, because when participants were allowed to use their preferred STW strategy in repeated trials, 50% of adults and 17% of OA patients used an asymmetric initial foot positioning in one or more trials

(Martin et al. 2013). Therefore, it is possible that asymmetric foot positioning is beneficial when the rising and walking task are merged, as the feet are then ideally placed to unload the rear foot during forward COM acceleration, initiating swing, but this hypothesis has not yet been investigated. There is also evidence that asymmetric loading of the limbs is a compensatory action to shorten the reaction time in case of a balance recovery in quiet stance (Blaszczyk et al. 2000).

The possible benefits and drawbacks of biomechanical asymmetry strategies in standing up, such as potential implications for long-term joint degeneration due to asymmetry in joint loading, have not yet been determined. Restricting asymmetry and preferred foot placement in the experimental protocol limits the available compensation of the participants, and therefore may not reflect daily life movements.

3.3. Restricted pacing: fixed end-goal

Most studies evaluated standing-up with standing as an end-goal (115/129 articles) (Fig. 1), rather than STW with walking as an end-goal. However, in daily life people often do not pause between a standing up motion and walking. Typical of STW strategies is that the first step is initiated before the body is fully extended, and people consistently use the same foot to initiate swing (Frykberg et al. 2012; Magnan et al. 1996). The motor control is also different: STW requires merging of a discrete task (standing up from a chair) with a rhythmic task (walking) and these two tasks overlap near the instant of seat-off. The mechanics of STS and STW are different: the vertical ground reaction force is significantly different between the two feet in the STW task, but not in STS (Magnan et al. 1996). In the anterior-posterior direction both STS and STW show a propulsive impulse followed by a braking impulse during standing-up. However, during the rising phase of STW, this impulse rapidly transitions to propulsion again to initiate walking (Magnan et al. 1996).

With these differences in timing, control and mechanics, the ageing process causes difficulty in merging the rising and walking tasks (Buckley et al. 2009; Frykberg et al. 2012). This difficulty in merging implies that a pause in between tasks could be a compensation for the lack of NMSK reserve. Clinical advice is to perform STW in a fluent motion, but in the case of instability caused by dizziness due to neurological or cardiovascular conditions, people may learn to compensate by pausing during the stabilization phase before continuing with walking or other activities (Chan et al. 1999).

As STS is a different task than STW both in mechanics and control, the lack of research in this latter movement limits the practical translation of research output to daily life practice. Research should aim to close this gap by investigating the STW motion.

Table 2
Compensation strategies for studies that permitted unrestricted arm movements in sit-to-stand or sit-to-walk.

Target group		push-off technique				paper outputs
		arm rest	seat	knees/ thighs	cane	
Healthy adults						
	Ellis et al. (1984)	X*				Knee forces
	Dolecka et al. (2015)	X		X		Observing incidence of arm use
Healthy elderly						
	Mazzà et al. (2004)	X		X		Observing incidence of arm use (instruction: avoid using arms)
	Leung and Chang (2009)	X			X	Analysing trunk angle
	Smith et al. (2019a)	X				Upper and lower limb muscle and joint loading
	Smith et al. (2019b)	X				Site-specific muscle weakness and standing up performance
OA elderly						
	Davidson et al. (2013)	X				Lower limb muscle activation (instruction: avoid using arms)
	Komaris et al. (2018)		X	X		Observing incidence of arm use

* not explicitly mentioned where participants pushed off.

4. STEP 2: Compensation for capacity

Step 1 showed the possible compensation strategies and limitations of experimental protocols. Appreciating these existing limitations, Step 2 is to capture the current knowledge on Compensation for Capacity. This form of compensation relates to task-performance enhancing recruitment of NMSK resources in response to a relatively high task demand.

4.1. Muscular capacity

Muscle strength and power reduces with age, which is one of the contributors to an inability to stand up. Muscle loss is site specific and likely related to daily life use (Fig. 3). Several methods have been used to quantify muscle strength in relation to standing-up: 1) isometric or isokinetic strength tests, 2) handgrip strength measures, 3) exercise-induced reduction in muscle strength, and 4) modelling.

Studies have found some relationships between strategies in standing up and *isometric and/or isokinetic strength* tests. Higher isokinetic strength of the knee extensors was associated with smaller trunk flexion during STW (Dehail et al. 2007), although this relation was not found for the isometric strength of the knee extensors during STS (Lundin et al. 1999). Moreover, there was no significant effect of the isokinetic strength of the knee flexors/extensors and dorsiflexors on the basis of the existence of a sudden stop in between rising and walking in the elderly (Dehail et al. 2007). Isometric hip extension strength measured on a dynamometer did not show a correlation with trunk flexion in STS (Lundin et al. 1999). However, when the hip extensor strength was determined by the maximum weight that could be lifted no more than one time with acceptable form, more hip extensor strength was associated with a more upright trunk at lift-off in STS (Gross et al. 1998). This latter study has its limitations in how the hip strength was derived, so this conclusion may not be robust.

Handgrip strength has proven to be a useful tool to identify people at risk of mobility limitations (Sallinen et al. 2010) as a surrogate for overall muscle strength (Sales et al. 2017). Lower handgrip strength is weakly but significantly correlated with a longer STS duration and with a larger trunk flexion before seat off (van Lummel et al. 2018). In the extension phase, the maximum angular velocity of the trunk was higher and the vertical velocity lower for people with lower handgrip strength. As relative muscular decline varies between people (Gross et al. 1998), these correlative results might not be relevant for large numbers of subjects.

Muscle strength reduction has been studied via exercise-induced muscle damage (Spyropoulos et al. 2013). The study showed that the duration of STS and maximum trunk flexion angle increased with reduced muscle strength, and peak ankle dorsiflexion, and knee extension and knee flexion angles during STS decreased due to a reduced joint range of motion. Also, the vertical ground reaction force decreased after induced muscle damage, which was reflected in the knee and hip moment and power reduction. As muscle damage can also result in pain, compensation strategies found in this study were likely implemented to reduce pain as well due to muscle strength reduction. Larger trunk flexion is a compensation strategy observed in OA patients to unload the knee during standing up (Section 5.4).

Musculoskeletal modelling is an excellent tool to support the research of muscle weakness and movement strategies (Bajelan and Azghani 2014; Bobbert et al. 2016; Caruthers et al. 2016). When experimental studies have measurement limitations, modelling can complement measurements and observations with movement simulations. For example, Bobbert et al. (2016) used a predictive four-link two-dimensional rigid body model with nine muscle–tendon actuators to investigate successful STS despite weakness of muscles. These simulations demonstrated that a reduced muscle strength of up to 45% (all muscles) can still lead to a successful task completion without the use of arms. However, the cost of rising (muscle activation squared as an indication of energy expenditure), was more than 2.5 times higher in the weakened simulations compared to the baseline model. Unfortunately, muscle weaknesses greater than 45% and selective muscle atrophy were not simulated, whereas higher measured muscle strength reductions of up to 58% in certain muscle groups in elderly women have been found (Gross et al. 1998). These results raise the question of whether introducing larger muscle strength reductions and muscle group specific reductions would have led to the (in) ability of arm-restricted rising of this model. In reality, people often use out-of-plane, asymmetric, and upper-lower-limb compensation, which cannot yet be modelled with the state-of-the-art predictive models (Kruk et al. 2021).

One study recently analysed the joint and muscle forces of standing up with and without the use of armrests using upper- and lower limb musculoskeletal models in STS for young, middle-aged, and older adults (Smith et al. 2019). Lacking actual strength measurements, the strength profiles of the musculoskeletal models were adjusted based on average values from literature: $-25 \pm 5\%$ force reduction for the upper limb, and $-37 \pm 9.7\%$ force reduction for lower limb. The peak glenohumeral joint reaction force while using the armrests was significantly higher in older compared to young adults, despite no difference of the hand reaction forces measured on the armrests. This could be the result of compensation by reorganisation, and/or a difference in shoulder anatomy. Their results confirm that older adults compensate in standing up without arms by reducing the knee joint and extensor loading and increased use of hip extensors and plantar flexors. Another study by the same group showed that selective muscle weakness of the serratus anterior shoulder muscle was a key determinant of mobility in STS, by simulating muscle weakness with an upper limb musculoskeletal model (Smith et al. 2019). By removing muscles from the model one by one, serratus anterior weakness proved to limit the movement most and required most compensatory actions from the other muscles, leading to high upper body joint reaction forces. Since the motion in this model is prescribed (measured kinematics), the model did not allow for realistic compensation (no altered trajectories).

To summarize, there are moderate relationships between lower-limb strength and rising strategy. Larger knee and hip extension strength, and larger hand grip strength are moderately related to reduced trunk flexion while standing up. Actively reducing muscle strength leads to increased trunk flexion, decreased ground reaction forces, and longer rise times. These moderate relationships indicate that lower-limb strength is an important but not the only contributing factor in strategy selection. Only one group evaluated the upper limb muscles and joint forces in standing up. Their results indicate that shoulder loading is higher in older adults than in young, which emphasizes the need to further evaluate the upper limb muscle strength in relation to compensation in standing up.

These experimental and modelling studies on muscular reserve in standing up, except for one, focussed on standing up without arm support. Moreover, the studies investigated effects of muscle strength mostly as an isolated variable, neglecting other confounding factors of capacity and movement objectives. Understanding compensation for muscular capacity, however, requires insight into the reserve of the task (capacity versus task demand), which has not yet been done.
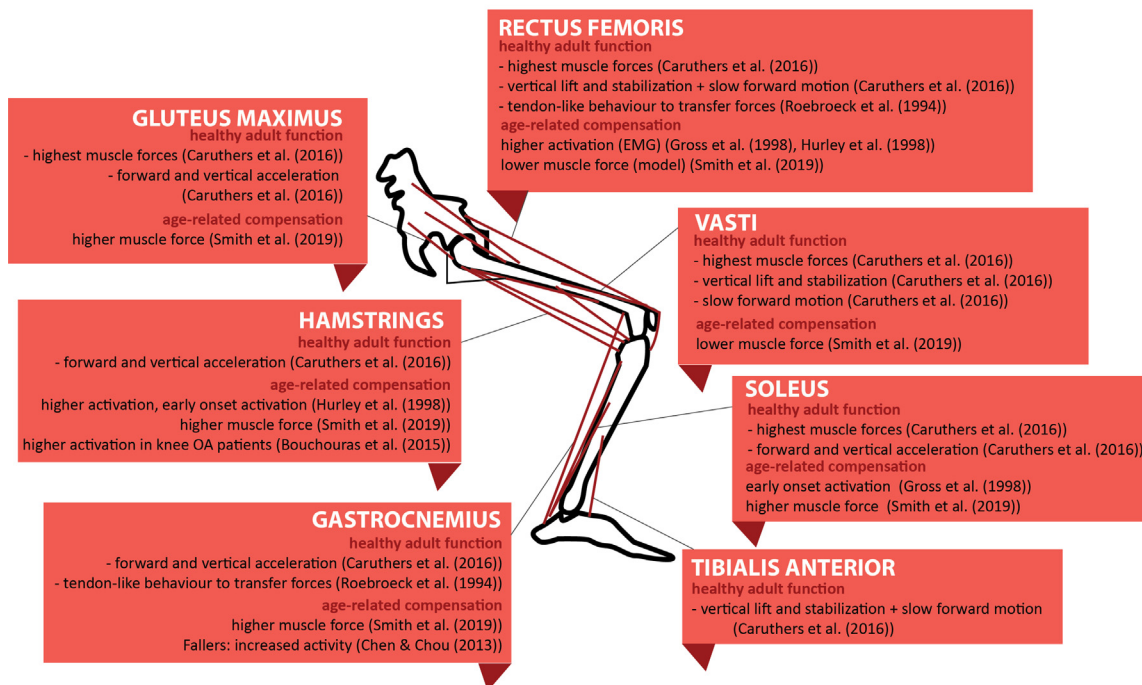
4.2. Neural capacity

The neural system consists of the (peripheral) nervous system and the sensory feedback system, which can be divided into the visual, auditory, vestibular systems, and proprioception.

a. Age-related decline in muscle capacity
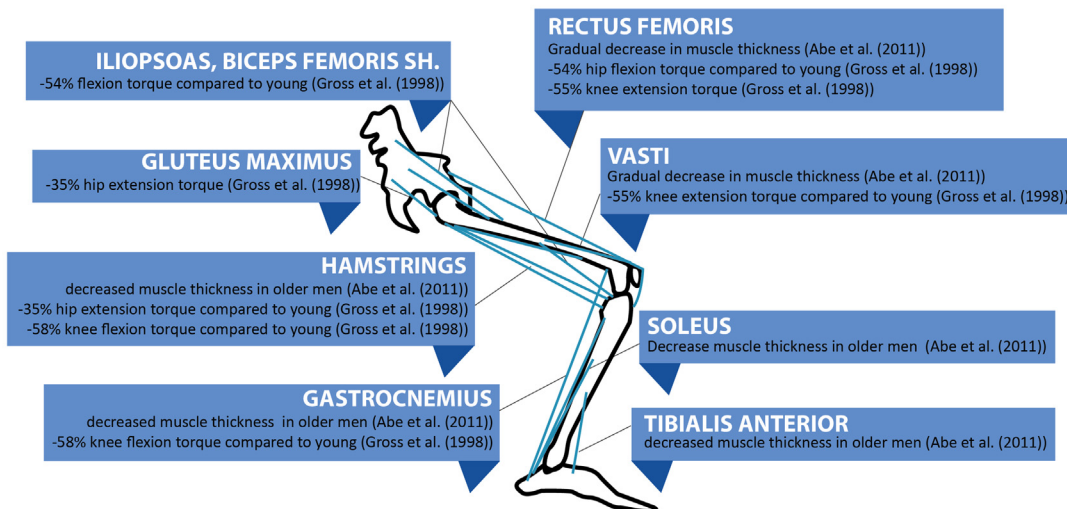
b. Age-related muscular compensation in sit-to-stand

Fig. 3. a) The loss of skeletal muscle mass is site-specific and is likely associated with the patterns of muscle activations that occur in daily life activities (Abe et al. 2011; Gross et al. 1998). b) Muscle recruitment in healthy adults and age-related compensation as described in relation to healthy adults. Using a three-dimensional inverse musculoskeletal model, Caruthers et al. (2016) determined the muscle forces and recruitment, and their individual contributions to the body centre of mass (COM) accelerations in the vertical and horizontal direction during STS without arm aid in healthy young adults. The gluteus maximus (GMAX) (hip extension), the quadriceps (specifically the vastus lateralis; knee extension), and the soleus (SOL; ankle plantarflexion) have the highest muscle forces in STS (Caruthers et al. 2016). The vertical and forward accelerations are driven by the GMAX, biceps femoris long head, adductor magnus, and the plantarflexors. The vertical lift and stabilization/slow forward motion is controlled by the quadriceps and tibialis anterior (TA). The monoarticular hip and knee extensors shorten while active and thus contribute to the extending moments of these joints, as do the biarticular hamstring muscles (HAM) (Roebroeck et al. 1994). However, the biarticular rectus femoris (RF) is active but has a very low shortening velocity, acting almost isometrically. It has been proposed that the function of RF demonstrates how muscles can act as tendons, transporting moments from the hip to the knee (Van Ingen Schenau 1989). The gastrocnemius (GAS) muscle may also transfer the moments from the knee to the ankle joint. This makes the co-contraction of the antagonist muscle an efficient way of transporting moments (Roebroeck et al. 1994). The age-related compensation findings are the results from studies that compared the muscle activation of older adults (incl. fallers) or adults with osteoarthritis to healthy adults in STS (Gross et al. 1998; Hurley, Rees, and Newham 1998; Smith et al. 2019; Chen and Chou 2013; Patsika, Kellis, and Amiridis 2011; Bouchouras et al. 2015).

Hurley et al. (1998) incorporated a measure of *proprioception* combined with a STW test (stand-up and level walking for 15.5 m) in young, middle-aged and elderly groups. In the proprioceptive test, participants were asked to reproduce a previously positioned knee angle. Joint position sense in elderly subjects was worse than in the middle-aged and young, and as age increased, the acuity decreased. The elderly also took significantly more time to perform the STW test, suggesting that there may be a

relationship between decline in joint position sense and movement performance in standing up, however there are certainly many other confounding factors, such as loss of muscle strength.

Older adults with poor binocular *visual acuity* show higher average foot pressures and absolute accelerations of the centre of pressure (indication of variation) during standing up compared to older adults with good visual binocular acuity (Shin et al. 2018). This result may indicate challenges with balance or a fear of falling in the poor vision acuity group. Fear of falling has previously been associated with poor vision acuity (Aartolahti et al. 2013). However, no significant differences in standing up kinematics have been found in adults between eyes open and eyes closed conditions of standing up (Assaiante et al. 2011; Tajali et al. 2013).

Proprioception and visual acuity have been shown to play a role in compensation for stability. Because these neural elements have been studied as isolated factors in restricted experimental set-ups, other relevant factors that might interact with the compensation strategies identified in these studies cannot be ruled out.

4.3. Skeletal capacity

Compensation for skeletal capacity in complex motor tasks is not often considered. Although the changed mechanics of bone might not directly translate to the motor control of complex motor tasks, the consequences of change will affect movement. As the consequences of a fall are more severe in the elderly (increased fracture risk), there is an increased fear of falling. This greater fear results in greater emphasis on stability as a movement objective in the motor control of movement. Moreover, wear of the joints, or osteoarthritis (OA), results in pain with loading, which puts more emphasis on pain avoidance in selecting a movement strategy. This is discussed in Section 5.

A combination of muscle stiffness, skeletal and joint changes results in a reduction of joint range of motion (ROM) with ageing. The age-related reduced hip flexion ROM approaches the maximal angle used in STS (Fotoohabadi et al. 2010). As there is little reserve, age-related compensation for hip flexion ROM capacity is likely in older adults. Elderly people also locate their feet more forward than young participants, which is more prevalent in elderly with OA than in healthy elderly participants and may be due to a reduced ROM in the knee and/or ankle joint (Papa and Cappozzo 2000).

5. STEP 3: Compensation for movement objectives

Thirdly, we looked at *compensation for movement objectives*, which relates to the emergence of different movement strategies due to a shift in the weighting of movement objectives. Biomechanical studies generally assume that humans select their movement strategies via a continuous optimization of a cost function minimizing an energy objective (Todorov and Jordan 2002). However, when performance is more important than energy efficiency, the relative movement objectives weighting likely changes. In older adults, psychological considerations, such as an increased emphasis on stability or pain avoidance may alter the applied motion strategy profoundly (Kruk et al. 2021). Four objectives were distinguished: energy, speed, stability, and pain. Whilst appreciating that there are limitations in the experiments presented in the literature, this section describes the current knowledge on compensation for movement objectives in standing up.

5.1. Energy

Recently a study was conducted using respiratory gas measurement to perform indirect calorimetry in STS (Nakagata et al. 2019).

Results show that in young male adults the energy expenditure in STS is 40% higher in slow (1–10 times per minute) standing up compared to normal (1–30 times per minute) standing up, and the energy expenditure increases with body height and weight (Nakagata et al. 2019). This result is in line with an earlier study that showed that the amplitude of integrated EMG signals of the vastus lateralis and the biceps femoris muscles are higher at slow compared to the fast movement conditions in STS (Bouchouras et al. 2015). Together, these results suggest that the commonly observed slower execution at self-selected speed of STS in older adults is unlikely to be an energetically economic strategy and that other movement objectives are important.

5.2. Speed

As the speed of the standing-up movement increases, the onset and maximum value of vertical momentum increases, whereas the horizontal momentum maintains the same timing and has a disproportionally smaller increase from slow to fast speeds (Pai and Rogers 1990; Vander Linden et al. 1994). Limiting the peak horizontal momentum at different speeds is a movement strategy to maintain equilibrium at the end of the task (standing balance) and was found in both young and older adults (Pai et al. 1994; Pai and Lee 1994). The quadriceps and erector spinae muscle activate earlier in fast movement conditions, while the tibialis anterior does not change in onset timing. Notably, this might be very different for the STW task, yet no studies have investigated this.

5.3. Stability

Due to a known increased incidence and more severe consequences of a fall, many older adults develop a fear of falling. This fear changes movement strategy, putting greater importance on stability.

The likelihood of balance loss is closely related to the horizontal position and velocity of the COM at lift-off (Pai and Rogers 1990). Anterior position of the COM or an increased forward COM velocity decreases the likelihood of a backward balance loss but increases the likelihood of a forward balance loss (Pavol and Pai 2002). Prior work suggests that adults compensate more to prevent a backward balance loss than a forward balance loss, which may be because falls are less likely from a forward balance loss (Pavol and Pai 2002; Hsiao and Robinovitch 1997). However, in STW, the elderly had a significantly lower horizontal momentum compared to the young, which restricted the anterior progression of the COM into walking (Buckley et al. 2009). This strategy could be an indication of stability considerations (movement objectives) or could also be related to the inability to generate this horizontal momentum (capacity). The lack of fluidity of STW has also been found in stroke patients (Osada et al. 2015; Dion et al. 2003) and it has been hypothesized that poor balance is one of the reasons why stroke patients are unable to begin walking fluently from the sitting position (Osada et al. 2015).

Older adults activate all involved ankle plantar flexors prior to the time of seat off, while young adults activate these muscles later (Gross et al. 1998; Smith et al. 2019). This difference in muscle activation timing may represent a stabilization strategy in the elderly. The peak magnitude of the muscle activations tends to be greater for older adults than for the young, and significantly different for the rectus femoris (Gross et al. 1998; Hurley et al. 1998) and the hamstrings (Hurley et al. 1998). These studies together suggest that elderly people activate their muscles at higher levels to accomplish the standing up movement. This higher activation is partly because older adults have strength deficits, and thus the relative effort is higher for older adults in the same movement. In addition, the higher activations in the hamstrings and

quadriceps are likely also due to co-contraction, which is thought to increase stiffness and joint stability, but also increase muscle fatigue (Hurley, Rees, and Newham 1998). Alterations in muscle activations demonstrate compensation by altered muscle recruitment.

Fallers (elderly people with a history of falling) have different movement strategies in standing-up compared to non-fallers; fallers have a longer rise time and a lower vertical ground reaction force in both STS and STW (Chorin et al. 2016; Chen et al. 2013). Also, STW fallers demonstrated compensation by taking smaller step-lengths at stance-off and a more anterior COM position at lift-off (Chen, Chang, and Chou 2013). Where non-fallers had a dorsiflexor moment at both lift-off and swing-off in STW, fallers had a plantar-flexor moment. These differences could be either related to reduced dorsiflexor strength in adults with a history of falls (Fukagawa et al. 1995), or due to the exaggerated trunk flexion strategy applied by fallers to improve stability compared to the momentum transfer strategy used by younger adults (Chen and Chou 2013). In STS, fallers showed compensation with an increased activation of the gastrocnemius lateralis. This activation is likely related to a compensation technique to improve stability.

Inadequate compensation after an external perturbation may result in a fall. Compensation for young and older adults after a perturbation does not differ. Insufficient concentric knee and hip extensor work prior to lift-off of the recovery step differentiates between falling and recovery (Pai et al. 2006). In addition, limiting the eccentric knee extensor work at the stance limb to slow rapid knee flexion is important to avoid a fall. Although the mechanisms of a fall after standing-up were similar between a group of young and older adults, the standing-up strategy was different between groups. Older adults had difficulty increasing the vertical momentum of their centre of mass at lift-off with less kinetic energy prior to this instant (Pai and Lee 1994). This difference in strategy may cause elderly adults to respond with insufficient knee extensor support to avoid a fall (Pai et al. 2006).

The studies mentioned in this section evaluated standing up strategies without the use of arms. As the use of arms can support adults in stability, more research on this compensation strategy for stability enhancement will be of value.

5.4. Pain

Pain is difficult to quantitively determine in experimental protocols. The most widely utilised methods are the WOMAC questionnaire and the visual analogue scale (VAS). The presence of pain substantially affects movement strategies.

The most prominent compensation of unilateral knee and hip OA patients (which is about 50% of the older population over 65 years) is asymmetry of movement (Turcot et al. 2012; Naili et al. 2018; Davidson et al. 2013; Eitzen et al. 2014; Lamontagne et al. 2012). Knee OA patients bear additional weight on the unaffected side by leaning the trunk (lateral trunk lean) (Turcot et al. 2012) or by using asymmetric arm movements (Martin et al. 2013). Pushing through the chair with the arm ipsilateral to the affected knee decreases the demand on lower limb extensors, while the arm on the contralateral side is used by swinging or pushing on the knee. Furthermore, knee OA patients showed significantly greater maximum trunk flexion (Turcot et al. 2012; Sagawa et al. 2017). Greater trunk flexion allows patients to shift their centre of mass closer to the knee joint to decrease the external moment about the knee. The rise time of moderate to severe OA patients is generally longer than adults, including the healthy elderly (Turcot et al. 2012; Patsika et al. 2011), with slower knee angular velocities. Moderate knee OA patients try to maintain the same movement trajectory as healthy individuals in standing up,

resulting in compensation via increased antagonist activation (Patsika et al. 2011; Davidson et al. 2013; Bouchouras et al. 2015, Bouchouras et al. 2019). This increased activation may increase knee stability, thus providing relief from pain and discomfort.

Pain avoidance can lead to a compensation long after the pain is mitigated or eliminated (Farquhar et al. 2008). Former stressors or pain in participants might therefore still influence current movement strategies, which the researcher should be aware of when studying compensation.

Asymmetry, altered muscle recruitment, and foot positioning play an important role in pain compensation. Altered trunk flexion strategies, which previously were shown to be related to muscle weakness, may also be related to pain avoidance. Incorporating unrestricted movement and a pain measure for previous or current experienced pain is therefore advised when analysing (age-related) movement strategies.

6. Conclusions

Compensation is a result of functional redundancy and plays a significant role in preventing and predicting movement impairments. Yet, this review showed that the experimental set-ups and musculoskeletal models in STS and STW studies generally exclude compensation by using restricted protocols and simplifications. Moreover, factors are mostly analysed in isolation, excluding confounding causes within capacity and/or movement objectives. These approaches can limit the generalization of the results.

Appreciating these limitations, compensation for the decline of muscular, neural, and skeletal capacity in standing up remains elusive, although there are indications that reduced knee and hip extension strength is compensated by a larger trunk flexion when no arms are used and that reduced visual acuity puts more emphasize on stability as a movement objective. Moreover, there is little reserve in hip joint range of motion for STS in older adults. Age-related compensation for movement objectives seems characterized by reduced emphasis on the energy objective, demonstrated by a slower self-selected speed which is a non-energetically economic strategy. Furthermore, there seems to be an increased emphasis on the stability objective, characterized by a lack of fluidity between standing and walking and increased co-contraction in elderly people. Lastly, compensation for pain was demonstrated by asymmetric leaning of the trunk, asymmetric arm push-off, greater maximum trunk flexion, and increased antagonist activation.

The following recommendations are made for future experimental protocols:

- Enabling unrestricted arm and foot movements in experimental protocols would better reflect daily-life activities. For clinical translation, the trunk and upper-limb joint loading for varying arm rise strategies (e.g. armrests, cane, knees, chair) should be determined.
- STS is a different task than STW both in mechanics and control; little research in this latter movement limits the practical translation of research output to daily life practice. Research should aim to close this gap by focussing on the STW motion.
- Asymmetries in limb trajectories, ground reaction force, and muscle activations are common in both young and elderly adults. The effects and possible benefits of biomechanical asymmetry strategies on joint loading throughout the body, and potential implications for long-term joint degeneration have yet to be quantified.
- Compensation for muscular capacity should be studied in the context of reserve, determining both the participants' capacity and the task demand.

- The effect of decline in the neural capacity (for example, sensor and motor noise, nerve conduction speed, proprioception) on compensation in standing up is largely unexplored and should be studied to gain a better understanding of movement limitations.
- Psychological priority changes, such as due to pain or fear of falling, and previous stressors and injuries are scarcely reported in studies on the control of complex motor tasks and should be considered for inclusion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

References

Aartolahti, Eeva, Häkkinen, Arja, Lönnroos, Eija, Kautiainen, Hannu, Sulkava, Raimo, Hartikainen, Sirpa, 2013. Relationship between functional vision and balance and mobility performance in community-dwelling older adults. Aging Clin. Exp. Res. 25 (5), 545–552.

Abe, Takashi, Sakamaki, Mikako, Yasuda, Tomohiro, Bemben, Michael G, Kondo, Masakatsu, Kawakami, Yasuo, Fukunaga, Tetsuo, 2011. Age-related, site-specific muscle loss in 1507 japanese men and women aged 20 to 95 years. J. Sports Sci. Med. 10 (1), 145.

Assaiante, Christine, Chabeauti, Pierre Yves, Sveistrup, Heidi, Vaugoyeau, Marianne, 2011. Updating process of internal model of action as assessed from motor and postural strategies in young adults. Hum. Mov. Sci. 30 (2), 227–237. https://doi.org/10.1016/j.humov.2010.05.007.

Bajelan, Soheil, Azghani, Mahmood Reza, 2014. Musculoskeletal modeling and simulation of three various sit-to-stand strategies : an evaluation of the biomechanical effects of the chair-rise strategy modification. 22, 627–44. https://doi.org/10.3233/THC-140834.

Blaszczyk, Janusz W, Prince, Francois, Raiche, Michel, Hébert, Réjean, 2000. Effect of ageing and vision on limb load asymmetry during quiet stance. J. Biomech. 33 (10), 1243–1248.

Bobbert, Maarten F, Kistemaker, Dinant A, Aurélio, Marco, Ackermann, Marko, 2016. Searching for strategies to reduce the mechanical demands of the sit-to-stand task with a muscle-actuated optimal control model. Clin. Biomech. 37, 83–90. https://doi.org/10.1016/j.clinbiomech.2016.06.008.

Bouchouras, Georgios, Patsika, Glykeria, Hatzitaki, Vassilia, Kellis, Eleftherios, 2015. Kinematics and knee muscle activation during sit-to-stand movement in women with knee osteoarthritis. Clin. Biomech. 30 (6), 599–607.

Bouchouras, Georgios, Sofianidis, George, Patsika, Glykeria, Kellis, Eleftherios, Hatzitaki, Vasileia, 2019. Women with knee osteoarthritis increase knee muscle co-contraction to perform stand to sit. Aging Clin. Exp. Res., 1–8

Boukadida, Amira, Piotte, France, Dehail, Patrick, Nadeau, Sylvie, 2015. Determinants of sit-to-stand tasks in individuals with hemiparesis post stroke: a review. Ann. Phys. Rehabil. Med. 58 (3), 167–172. https://doi.org/10.1016/j.rehab.2015.04.007.

Buckley, Thomas, Pitsikoulis, Chris, Barthelemy, Ernest, Hass, Chris J, 2009. Age impairs sit-to-walk motor performance. J. Biomech. 42 (14), 2318–2322.

Caruthers, Elena J, Thompson, Julie A, Chaudhari, Ajit M W, Schmitt, Laura C, Best, Thomas M, Saul, Katherine R, Siston, Robert A, 2016. Muscle forces and their contributions to vertical and horizontal acceleration of the center of mass during sit-to-stand transfer in young, healthy adults. J. Appl. Biomech. 32 (5), 487–503.

Chan, Donna, Laporte, Diane M., Sveistrup, Heidi, 1999. "Art 2:" 62 (February), 64–68.

Chen, Tzurei, Chang, Chien Chi, Chou, Li Shan, 2013. Sagittal plane center of mass movement strategy and joint kinetics during sit-to-walk in elderly fallers. Clin. Biomech. 28 (7), 807–812. https://doi.org/10.1016/j.clinbiomech.2013.07.002.

Chen, Tzurei, Chou, Li Shan, 2013. Altered center of mass control during sit-to-walk in elderly adults with and without history of falling. Gait Posture 38 (4), 696–701. https://doi.org/10.1016/j.gaitpost.2013.03.007.

Cheng, Y.J., Hootman, J.M., Murphy, L.B., Langmaid, G.A., Helmich, C.G., 2010. Prevalence of doctor-diagnosed arthritis and arthritis-attributable activity limitation-United States, 2007–2009. Morb. Mortal. Wkly Rep. 59 (39), 1261–1265.

Chorin, Frédéric, Cornu, Christophe, Beaune, Bruno, Frère, Julien, Rahmani, Abderrahmane, 2016. Sit to stand in elderly fallers vs non-fallers: new insights from force platform and electromyography data. Aging Clin. Exp. Res. 28 (5), 871–879. https://doi.org/10.1007/s40520-015-0486-1.

Davidson, Bradley S., Judd, Dana L., Thomas, Abbey C., Mizner, Ryan L., Eckhoff, Donald G., Stevens-Lapsley, Jennifer E., 2013. Muscle activation and coactivation during five-time-sit-to-stand movement in patients undergoing total knee arthroplasty. J. Electromyogr. Kinesiol. 23 (6), 1485–1493. https://doi.org/10.1016/j.jelekin.2013.06.008.

Dehail, P., Bestaven, E., Muller, F., Mallet, A., Robert, B., Bourdel-Marchasson, I., Petit, J., 2007. Kinematic and electromyographic analysis of rising from a chair during a '' sit-to-walk '' task in elderly subjects: role of strength. Clin. Biomech. 22, 1096–1103. https://doi.org/10.1016/j.clinbiomech.2007.07.015.

Dion, Lise, Malouin, Francine, Mcfadyen, Bradford, Richards, Carol L., 2003. Assessing mobility and locomotor coordination after stroke with the rise-to-walk task. Neurorehabil. Neural Repair 17 (2), 83–92. https://doi.org/10.1177/0888439003017002002.

Dolecka, Urszula E., Ownsworth, Tamara, Kuys, Suzanne S., 2015. Comparison of sit-to-stand strategies used by older adults and people living with dementia. Arch. Gerontol. Geriatr. 60 (3), 528–534. https://doi.org/10.1016/j.archger.2014.12.007.

Eitzen, Ingrid, Fernandes, Linda, Nordsletten, Lars, Snyder-Mackler, Lynn, Risberg, May Arna, 2014. Weight-bearing asymmetries during sit-to-stand in patients with mild-to-moderate hip osteoarthritis. Gait Posture 39 (2), 683–688. https://doi.org/10.1016/j.gaitpost.2013.09.010.

Ellis, M.I., Seedhom, B.B., Wright, V., 1984. Forces in the knee joint whilst rising from a seated position. J. Biomed. Eng., 113–120.

Farquhar, Sara J, Reisman, Darcy S, Snyder-Mackler, Lynn, 2008. Persistence of altered movement patterns during a sit-to-stand task 1 year following unilateral total knee arthroplasty. Phys. Ther. 88 (5), 567–579. https://doi.org/10.2522/ptj.20070045.

Fotoohabadi, Mohammad R., Tully, Elizabeth A., Galea, Mary P., 2010. Kinematics of rising from a chair: image-based analysis of the sagittal elderly people who are healthy. Phys. Ther. 90 (4), 561–571.

Frykberg, Gunilla E., Thierfelder, Tomas, Cristina åberg, Anna, Halvorsen, Kjartan, Borg, Jörgen, Hirschfeld, Helga, 2012. Impact of stroke on anterior-posterior force generation prior to seat-off during sit-to-walk. Gait Posture 35 (1), 56–60. https://doi.org/10.1016/j.diagmicrobio.2012.08.027.

Fukagawa, Naomi K, Wolfson, Leslie, Judge, James, Whipple, Robert, King, Mary, 1995. Strength is a major factor in balance, gait, and the occurrence of falls. J. Gerontol. A Biol. Sci. Med. Sci. 50 (Special_Issue), 64–67.

Gilleard, Wendy, Crosbie, Jack, Smith, Richard, 2008. Rising to stand from a chair: symmetry, and frontal and transverse plane kinematics and kinetics. Gait Posture 27, 8–15. https://doi.org/10.1016/j.gaitpost.2006.11.002.

Gross, M.M., Stevenson, P.J., Charette, S.L., Pyka, G., Marcus, R., 1998. Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. Gait Posture 8, 175–185.

Hsiao, Elizabeth T, Robinovitch, Stephen N, 1997. Common protective movements govern unexpected falls from standing height. J. Biomech. 31 (1), 1–9.

Hughes, M.A., Schenkman, M.L., 1996. Chair rise strategy in the functionally impaired elderly. J. Rehabil. Res. Dev. 33 (4), 409–412.

Hurley, Michael V, Rees, Joanne, Newham, Di J, 1998. Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle-aged and elderly subjects. Age Age. 27 (1), 55–62.

Schenau, Ingen, Van, Gerrit Jan, 1989. On the action of bi-articular muscles, a review. Netherlands J. Zool. 40 (3), 521–543.

Janssen, W., Bussmann, H.J., Stam, H.J., 2002. Determinants of the sit-to-stand movement : a review 82 (9), 866–79.

Kawagoe, Shoichi, Tajima, Naoya, Chosa, Etsuo, 2000. Biomechanical analysis of effects of foot placement with varying chair height on the motion of standing up. J. Orthopaedic Sci. 5 (2), 124–133.

Khemlani, M.M., Carr, J.H., Crosbie, W.J., 1999. Muscle synergies and joint linkages in sit-to-stand under two initial foot positions. Clin. Biomech. 14 (4), 236–246.

Komaris, Dimitrios-Sokratis, Govind, Cheral, Murphy, Andrew, Ewen, Alistair, Riches, Philip, 2018. Identification of movement strategies during the sit-to-walk movement in patients with knee osteoarthritis. J. Appl. Biomech. 34 (2), 96–103.

van der Kruk, Eline, Silverman, Anne K., Koizia, Louis, Reilly, Peter, Fertleman, Michael, Bull, Anthony M.J., 2021. Age-related compensation: neuromusculoskeletal capacity, reserve & movement objectives. J. Biomech. 122, 110385.

Lamontagne, Mario, Beaulieu, Mélanie L., Varin, Daniel, Beaulé, Paul E., 2012. Lower-limb joint mechanics after total hip arthroplasty during sitting and standing tasks. J. Orthop. Res. 30 (10), 1611–1617. https://doi.org/10.1002/jor.22127.

Linden, Darl W., Vander, Denis Brunt, McCulloch, Marina U., 1994. Variant and invariant characteristics of the sit-to-stand task in healthy elderly adults. Arch. Phys. Med. Rehabil. 75 (6), 653–660. https://doi.org/10.1016/0003-9993(94)90188-0.

van Lummel, Rob C., Evers, Jordi, Niessen, Martijn, Beek, Peter J., van Dieën, Jaap H., 2018. Older adults with weaker muscle strength stand up from a sitting position with more dynamic trunk use. Sensors (Switzerland) 18 (4), 1–12. https://doi.org/10.3390/s18041235.

Lundin, T.M., Jahnigen, D.W., Grabiner, M.D., 1999. Maximum trunk flexion angle during sit to stand is not determined by knee or trunk-hip extension strength in healthy older adults. J. Appl. Biomech. 15, 233–241.

Magnan, André, McFadyen, Bradford J., St-Vincent, Guy, 1996. Modification of the sit-to-stand task with the addition of gait initiation. Gait Posture. https://doi.org/10.1016/0966-6362(95)01048-3.

Martin, Jeff, Garn, Alex, Studies, Sport, Rouge, Baton, 2013. Note : This Article Will Be Published in a Forthcoming Issue of The Sport Psychologist. This Article

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Mazzà, Claudia, Benvenuti, Francesco, Bimbi, Carlo, Stanhope, Steven J, 2004. Association between subject functional status, seat height, and movement strategy in sit-to-stand performance. J. Am. Geriatr. Soc. 52 (10), 1750–1754.

Naili, E., Broström, Eva W., Gutierrez-farewik, Elena M., Schwartz, Michael H., 2018. The centre of mass trajectory is a sensitive and responsive measure of functional compensations in individuals with knee osteoarthritis performing the five times sit-to-stand test. Gait & Posture 62, 140–145. https://doi.org/10.1016/j.gaitpost.2018.03.016.

Nakagata, Takashi, Yamada, Yosuke, Hatamoto, Yoichi, Naito, Hisashi, 2019. Energy expenditure of a single sit-to-stand movement with slow versus normal speed using the different frequency accumulation method. Medicina 55 (3), 77.

Norman-Gerum, Valerie, McPhee, John, 2020. Comprehensive description of sit-to-stand motions using force and angle data. J. Biomech. 112, 110046.

Osada, Yuji, Yamamoto, Sumiko, Fuchi, Masako, Ibayashi, Setsuro, 2015. Sit-to-walk task in hemiplegic stroke patients: relationship between movement fluidity and the motor strategy in initial contact. J. Japanese Phys. Therapy Assoc. Vol18_002.

Pai, Y.C., Rogers, Mark W, 1990. Control of body mass transfer as a function of speed of ascent in sit-to-stand. Med. Sci. Sports Exerc. 22 (3), 378–384.

Pai, Yi-Chung, Naughton, B.J., Chang, Rowland W, Rogers, M.W., 1994. Control of body centre of mass momentum during sit-to-stand among young and elderly adults. Gait Posture 2 (2), 109–116.

Pai, Yi Chung, Lee, Wynne A., 1994. Effect of a terminal constraint on control of balance during sit-to-stand. J. Mot. Behav. 26 (3), 247–256. https://doi.org/10.1080/00222895.1994.9941680.

Pai, Yi Chung, Yang, Feng, Wening, Jason D., Pavol, Michael J., 2006. Mechanisms of limb collapse following a slip among young and older adults. J. Biomech. 39 (12), 2194–2204. https://doi.org/10.1016/j.jbiomech.2005.07.004.

Papa, Elisabetta, Cappozzo, Aurelio, 2000. Sit-to-stand motor strategies investigated in able-bodied young and elderly subjects. J. Biomech. 33 (9), 1113–1122. https://doi.org/10.1016/S0021-9290(00)00046-4.

Patsika, Glykeria, Kellis, Eleftherios, Amiridis, Ioannis G., 2011. Neuromuscular efficiency during sit to stand movement in women with knee osteoarthritis. J. Electromyogr. Kinesiol. 21 (5), 689–694. https://doi.org/10.1016/j.jelekin.2011.05.006.

Pavol, Michael J., Pai, Yi Chung, 2002. Feedforward adaptations are used to compensate for a potential loss of balance. Exp. Brain Res. 145 (4), 528–538. https://doi.org/10.1007/s00221-002-1143-4.

Roebroeck, M.E., Doorenbosch, C.A.M., Harlaar, J., Jacobs, R., Lankhorst, G.J., 1994. Biomechanics and muscular activity during sit-to-stand transfer. Clin. Biomech. 9 (4), 235–244.

Rolfson, Darryl B, Majumdar, Sumit R., Tsuyuki, Ross T., Tahir, Adeel, Rockwood, Kenneth, 2006. Validity and reliability of the edmonton frail scale. Age Ageing 35 (5), 526–529.

Sagawa, Yoshimasa, Bonnefoy-Mazure, Alice, Armand, Stéphane, Hoffmeyer, Pierre, Suva, Domizio, Turcot, Katia, 2017. Individuals with knee osteoarthritis exhibit altered movement patterns during the sit-to-stand task. Mov. Sport Sci. - Science & Motricité, 98, 39–49. https://doi.org/10.1051/sm/2017004.

Sales, Myrla, Levinger, Pazit, Polman, Remco, 2017. Relationships between self perceptions and physical activity behaviour, fear of falling, and physical function among older adults. Eur. Rev. Aging Phys. Act. 14 (1), 17.

Sallinen, Janne, Stenholm, Sari, Rantanen, Taina, Heliövaara, Markku, Sainio, Päivi, Koskinen, Seppo, 2010. Hand-grip strength cut points to screen older persons at risk for mobility limitation. J. Am. Geriatr. Soc. 58 (9), 1721–1726.

Scarborough, Donna Moxley, McGibbon, Chris A., Krebs, David E., 2007. Chair rise strategies in older adults with functional limitations. J. Rehabil. Res. Dev. 44 (1), 33. https://doi.org/10.1682/JRRD.2005.08.0134.

Shia, Victor, Moore, Talia Yuki, Holmes, Patrick, Bajcsy, Ruzena, Vasudevan, Ram, 2018. Stability basin estimates fall risk from observed kinematics, demonstrated on the sit-to-stand task. J. Biomech. 72, 37–45. https://doi.org/10.1016/j.jbiomech.2018.02.022.

Shin, Sun-Shil, An, Duk-Hyun, Yoo, Won-Gyu, 2018. Comparison of foot pressure and center of force during sit-to-stand and stand-to-sit movements in older adults with good and poor visual acuity. Top. Geriatric Rehabil. 34 (1), 82–86.

Smith, Samuel H.L., Reilly, Peter, Bull, Anthony M.J., 2019a. A musculoskeletal modelling approach to explain sit-to-stand difficulties in older people due to changes in muscle recruitment and movement strategies. J. Biomech. 109451.

Smith, S.H.L., Reilly, P., Bull, A.M.J., 2019b. Serratus anterior weakness is a key determinant of arm-assisted standing difficulties. Med. Eng. Phys.

Spyropoulos, Giannis, Tsatalas, Themistoklis, Tsaopoulos, Dimitrios E., Sideris, Vasilios, Giakas, Giannis, 2013. Biomechanics of sit-to-stand transition after muscle damage. Gait Posture 38 (1), 62–67. https://doi.org/10.1016/j.gaitpost.2012.10.013.

Tajali, Shirin, Negahban, H., Shaterzadeh, M.J., Mehravar, M., Salehi, R., Narimani, R., Parnianpour, M., 2013. Multijoint coordination during sit-to-stand task in people with non-specific chronic low back pain. Biomed. Eng.: Appl., Basis Commun. 25 (01), 1350010. https://doi.org/10.4015/S1016237213500105.

Todorov, Emanuel, Jordan, Michael I., 2002. Optimal feedback control as a theory of motor coordination. Nat. Neurosci. 5 (11), 1226–1235.

Turcot, Katia, Armand, Stéphane, Fritschy, Daniel, Hoffmeyer, Pierre, Suvà, Domizio, 2012. Sit-to-stand alterations in advanced knee osteoarthritis. Gait Posture 36 (1), 68–72. https://doi.org/10.1016/j.gaitpost.2012.01.005.

UN, 2019. United Nations. 2019.