CaReMoOC: Capacity, Reserve, Movement Objectives, and Compensation. A proposed framework to describe mechanisms of movement limitations, demonstrated for ageing.

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Abstract

The prevention, mitigation and treatment of movement impairments, ideally, requires early diagnosis or identification. As the human movement system has physiological and functional redundancy, movement limitations do not promptly arise at the onset of physical decline. A such, prediction of movement limitations is complex: it is unclear how much decline can be tolerated before movement limitations start and how humans select compensatory movement strategies for a task. Adding to the challenge is the lack of general applicable and consensus terminology on movement limitations. Currently, the term 'homeostatic reserve' or 'physiological reserve' is used to refer to the redundancy of the human biological system, but this does not describe the redundancy in the muscle architecture of the human body. This article therefore proposes CaReMoOC, a framework incorporating neuromusculoskeletal capacity (accumulation of neuromusculoskeletal resources over the lifespan), reserve (task-specific difference between capacity and task demand), movement objectives (considerations made to plan a movement), and compensation (use of NMSK resources to respond to the task demand). Two forms of compensation are Compensation for Capacity, when capacity does not meet the task demands, and Compensation for Movement Objectives, when the movement is changed due to for example a fear of falling. This article demonstrates the framework for healthy ageing, providing an overview of age-related capacity decline (neural, skeletal, muscular system) and shifted weighting of movement objectives (energy, pain, stability, speed) relevant for experimental and modelling research in biomechanics and motor control. CaReMoOC provides a means to communicate hypotheses and theories on movement impairments and limitations. To predict movement limitations, we need to find ways to quantify NMSK reserve.

Keywords: Mobility impairments, Neuromusculoskeletal models, Rehabilitation, optimal control theory, frailty

1. Introduction

Consistently low birth rates and higher life expectancy are transforming society, resulting in the proportional and absolute increase in an ageing population. Rapid ageing is occurring world-wide, so that by 2050 all regions except for Africa will have at least 25% of their population over 60 years old; the proportion of people aged 80 or over will have tripled by that time (UN, 2019). Ageing is often accompanied by a decrease in mobility, which can lead to loss of independence, inability to work, and social exclusion.

Ideally, movement limitations would be recognized and prevented at an early stage. Mechanisms that contribute to mobility impairments are therefore major research topics in the fields of physiology, biomechanics, and motor control. While the fields of biomechanics and motor control seek to understand the mechanisms of age-related mobility decline by understanding forces, deformation, control, and motion of biological systems, the field of physiology focusses on the biological processes. Combining the knowledge from these different fields seems inevitable to understand age-related movement impairments.

Daily life activities such as walking, standing up from a chair, or ascending stairs are complex motor tasks which involve subtle muscle control and trajectory planning (Caruthers et al., 2016; Harper, Wilken, & Neptune, 2018; Winter, 1995). As the human movement system has physiological and functional redundancy, movement limitations do not promptly arise at the onset of physical decline (Lipsitz, 2002). Moreover, movement trajectories can be executed with a variety of alternative muscle recruitments to compensate for decline, such as different levels of co-contraction. The execution of the task could also be changed, for example, standing up from a chair using the armrests versus without, or walking versus running. This makes prediction of movement limitations more complex as it is unclear how much decline can be tolerated before movement limitations begin and how humans select compensatory movement strategies for a task.

Selection of movement strategies is generally assumed to occur through a continuous optimization of a cost function (optimal control theory) (Todorov & Jordan, 2002). While energy-related costs have been found to be the primary driver for broad categories of gait (F. C. Anderson & Pandy, 2001; Cavagna & Franzetti, 1986; Hoyt & Taylor, 1981; Kuo, 2001; Minetti, Ardigo, Reinach, & Saibene, 1999), it is probably not the only driver (Malatesta et al., 2003; Raynor, Yi, Abernethy, & Jong, 2002). Especially in ageing and neuromuscular deficiencies, it is likely that humans place more emphasis on other objectives, such as stability due to an increased fear of falling. The exact cost-function that humans optimize for in their daily movements is not known. However, strategy selection plays a critical part in movement impairments.

In clinic, the term 'homeostatic reserve' or 'physiological reserve' is used to refer to the redundancy of the human biological system that can compensate for age and disease-related changes (Clegg, Young, Iliffe, Rikkert, & Rockwood, 2013). The purpose of the term is to indicate whether a patient is likely to recover from an insult and to determine frailty (Rockwood et al., 2005). This term does however not describe or quantify the redundancy in the muscle architecture of the human body, which involves compensation either through altered kinematics or muscle recruitment. Terms such as physiological capacity (Oseid, 1973), musculoskeletal reserve (Bull, Cleather, & Southgate, 2008), and musculoskeletal capacity (Nygård, Luopajärvi, Cedercreutz, & Ilmarinen, 1987) have been used, but a general understanding and definition of these terms in the fields of biomechanics and motor control is lacking. Generally applicable and consensus terminology on movement limitations would enable discussion and enhance research and quantification in this area.

This article therefore proposes a general framework to describe mechanisms of movement limitations proposing definitions of neuromusculoskeletal (NMSK) capacity, reserve, movement objectives, and compensation (CaReMoOC from now on). After introducing the general framework, this article concentrates on applying CaReMoOC to ageing by providing an overview of the age-related declining factors (physiology) that should be accounted for in age-related human movement studies in the fields of biomechanics and motor control. Apart from ageing, we also see value for this general framework on movement limitations to be used in other cohorts such as patients with muscular disease, amputees, or rehabilitation.

2. CaReMoOC: Capacity, Reserve, Movement Objectives, and Compensation

We propose the CaReMoOC framework incorporating NMSK Capacity, Reserve, Movement Objectives, and Compensation to describe movement limitations (Fig. 1). Capacity refers to the physiological abilities of the human body. Reserve refers to the task-specific difference between the capacity and task demand. If the selection of a movement strategy within the redundancy of NMSK capacity is the outcome of human optimization, movement objectives refer to the criteria considered in this optimization. Compensation refers to altered selection of movement strategies compared to a baseline, as a result of a reduction in reserve. Each of these definitions is clarified separately below.

2.1 Neuromusculoskeletal capacity

Neuromusculoskeletal capacity is defined as the physiological abilities of the neuromusculoskeletal system. Capacity accumulates due to genetic and/or environmental factors up to a point at which age-related decline sets in (Fig. 1a) (Kirkwood, 2005). A higher peak (or plateau) capacity mitigates the effects of decline caused by ageing or age-related diseases and the rate of decline can be adjusted through environmental factors (Warburton, Nicol, & Bredin, 2006).

Age-related decline of neuromusculoskeletal capacity is a result of structural changes of the neural, muscular, and skeletal (including soft tissues) systems, which are reviewed in detail in Section 3-5. NMSK capacity does not directly account for changes in the endocrine, immune, cardiovascular, respiratory, renal, or brain systems. The level of NMSK capacity determines whether an individual can overcome a stressor such as the consequences of a fall. Therefore key factors to be considered are peak capacity and slope of decline (Clegg et al., 2013).

2.2 Neuromusculoskeletal reserve

We define NMSK reserve as task specific and as the difference between the capacity and the task demands (Fig. 1b). Reserve describes whether we can execute a task and how much reserve there is left before the onset of task inability. As task requirements vary over the duration of the task, so does reserve, therefore, inability may occur for only a portion of the task but still results in task failure. For example, in standing up, the point of lift off from the chair has the highest task demand and the reserve for this part of the task is therefore smallest. It is likely that this part of the task execution will become impaired first, unless there is room for compensation, described later.

2.3 Movement objectives

Within the redundancy of capacity and reserve, humans both consciously and unconsciously decide on movement strategies. To reach the movement goal (e.g. standing up), there are several feasible strategies within the capacity to reach this goal each with their own task demands (e.g. standing up with or without using arms) (Fig. 1c). The applied motion strategy of humans is probably a consideration of metabolic energy, velocity, stability (safety), and/or pain avoidance, which will be jointly referred to as the movement objectives (Fig. 1d). Each strategy can attribute a different weighting to these movement objectives, resulting in different movement strategies.

Although movement objectives are not age dependent, the relative weighting of these objectives most likely are, thus resulting in different movement strategies at different ages. Elderly people may for example put more emphasis on stability due to the more severe consequences of a fall. The movement objectives and their relative weighting are a multi-objective function resulting in a weighted average. Humans probably make comparative assessments of movement objectives based on the task goal, their capacity, and psychological reasons such as fear of falling, pain, or an unknown environment (Papa & Cappozzo, 2000).

2.4 Neuromusculoskeletal compensation

Compensation is defined as an alteration in movement strategy in relation to a baseline (e.g. previous state or a control group). We distinguish two cases of compensation:

- Compensation for Capacity: relates to task-performance enhancing recruitment of NMSK recourses in response to a relatively high task demand (Fig. 1d).
- Compensation for Movement Objectives: relates to the emergence of different movement strategies due to a shift in the weighting of movement objectives (Fig. 1d).

In the ideal case, the movement-enhancing compensation is sufficient to meet the goal. If compensation no longer enables the execution of the task at hand, inability and mobility limitations will arise (Fig. 1b).

Capacity determines whether and which compensation strategies are available. Compensation and capacity are therefore overlapping and interacting. Individuals with greater capacity have more room to deploy effective compensation strategies. But compensation strategies can also be detrimental when they result in a habitual over- or underuse of physiological abilities. Elderly people can end up in a negative cycle (cycle of frailty), which accelerates decline of capacity (Xue, 2011). A similar

mechanism is prevalent in the young after traumatic incidents. Athletes with a prior history of Anterior Cruciate Ligament (ACL) injury, for example, have increased risk of a second ACL injury and are more likely to develop early cartilage degeneration (knee osteoarthritis) as a result of insufficient or detrimental compensation strategies (Barenius et al., 2014; Cinque, Dornan, Chahla, Moatshe, & LaPrade, 2018; Schmitt, Paterno, & Hewett, 2012). The compensation applied after a stressor, for example asymmetry in gait to unload the involved side, can permanently change movement strategies. Such asymmetry could cause underuse of the involved side and overuse of the non-involved side, thereby putting capacity into decline in the long-term.

Within compensation we propose two forms or levels: selection and reorganization. Although these forms are not exclusive and can co-occur, it is important to recognize that multiple forms or levels of compensation exist (Cabeza et al., 2018):

- <u>Compensation by selection</u>: people can complete tasks using a variety of strategies to retain mobility including upper limb to lower limb compensations and postural changes. Compensation by selection is a variation in the planned movement trajectory. This compensation strategy is observable and can be expressed with the kinematics of the motion. Examples of compensation by selection are using the arms for standing up, using the handrail when climbing stairs, walking with a walking aid, widening the base of support in gait, or running with shorter step lengths.

- <u>Compensation by reorganization:</u> this form of compensation engages the altered selection of muscle recruitment. This form of compensation co-occurs when compensation by selection is apparent. However, as there is a redundancy in the muscle architecture of the human body, compensation by reorganization can also occur without a change in trajectory. A possible need of reorganization in healthy ageing could be the relative difference in decline of muscle strength between muscle groups (Abe et al., 2011; Gross, Stevenson, Charette, Pyka, & Marcus, 1998). An example of this form of compensation is co-contraction, which is a strategy that can be executed to increase stability through changes only in muscle recruitment, rather than changes in kinematics.
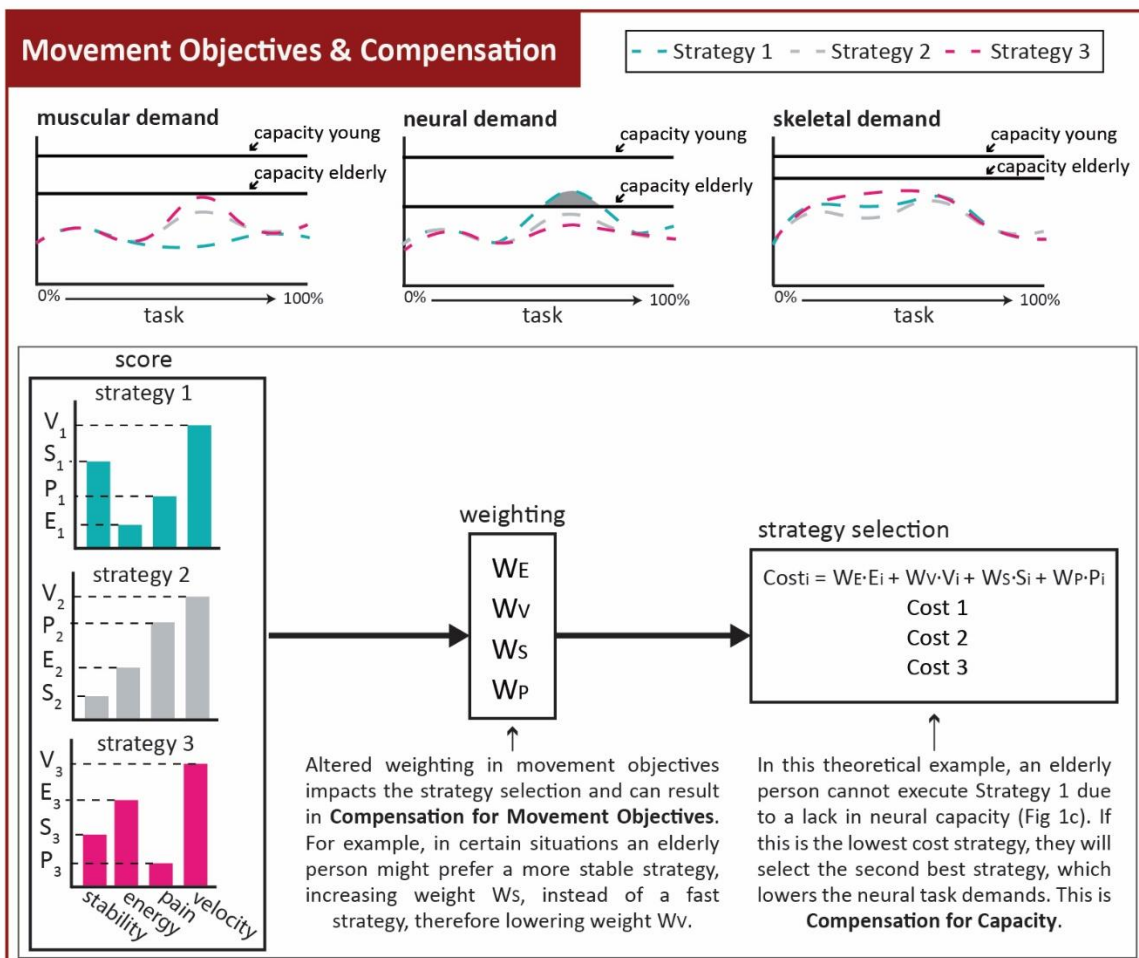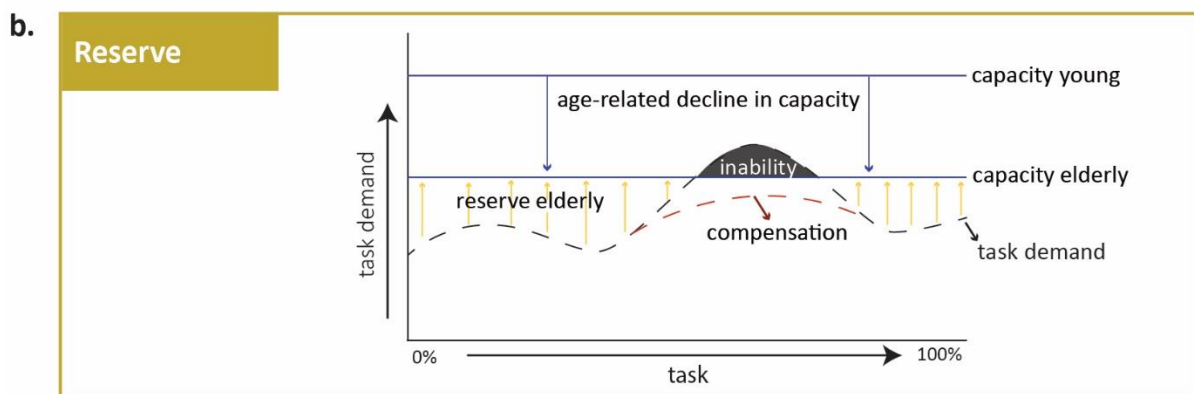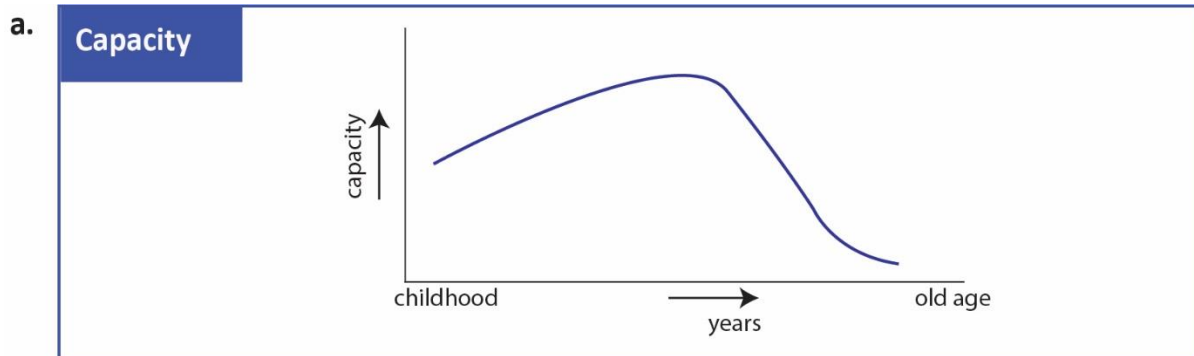
FIGURE 1: *Overview of CaReMoOC. (theoretical task)*

a.) Neuromuscular capacity accumulates due to genetic and/or environmental factors up to a point at which age-related decline sets in. Lifestyle choices such as exercise, nutrition, drugs and/or alcohol use, together with illness and genetics determine the peak and slope of capacity curve.

b.) Reserve is the difference between the capacity and the task demands. Capacity is defined as the physiological abilities of the neuromusculoskeletal system, in this case available for this task. If the reserve cannot meet the task demands, compensation will occur which changes the task demands while achieving the same goal.

c) The movement goal is the aim of the task (e.g. standing up from a chair) and has certain inherent constraints, such as gravity, not falling over, or avoiding objects. Within the capacity there are several possible movement strategies, each with their own task demands. (c) gives a theoretical task-specific overview of capacity separated into its main components: neural, skeletal, and muscular capacity. Multiple movement strategies have alternative task demands for each component of capacity and the systems can compensate for each other. Note that within each of the components there are sub-components for which these same concepts hold. For example, in the muscular capacity we could distinguish between the lower and upper body muscles, muscle groups, or individual muscles where different strategies result in different task demands on each of the sub-components. In this theoretical example, Strategy 1 cannot be executed by an elderly person due to a lack of neural capacity, and Strategy 3 can only just be executed by an elderly person due to zero reserve in muscular capacity.

d) These strategies can each be assigned a score on the movement objectives (Energy, Velocity, Stability, and Pain). Combining these scores with the weights of movement objectives in a multi-objective function results in an overall score. Based on the optimal control theory, the strategy with the lowest score will be selected. Compensation for capacity occurs when capacity does not meet the task demands of the lowest cost strategy (global minimum), the next best strategy will be selected (local minimum). Compensation for Movement Objectives occurs when, compared to a baseline, the choice in strategy has changed due to altered weighting of movement objectives.]

3. CaReMoOC for ageing

CaReMoOC can be used to communicate ideas and results regarding age-related movement limitations. Not all parts of CaReMoOC are easily quantifiable within biomechanical or motor control experimental designs. Many studies have therefore focused on an isolated variable and investigated how participants with high or low levels of these variables differ in their movements. This section provides an overview of the components and average onset and slope of age-related decline in capacity and compensation relevant for biomechanics and motor control. The aim of this section is not to propose that all elements of capacity and compensation should be incorporated in experimental protocols, however, being aware of the neglected parts of age-related changes may improve interpretation of experimental results. This section may be used as a guideline to determine what elements should be accounted for.

3.1 Compensation for capacity

Age-related decline in neuromusculoskeletal capacity can be divided separately into decline in neural, muscular and skeletal capacity. This section describes these age-related changes and considers how they can be measured.

3.1.1 Neural capacity

The neural system consists of the peripheral and central nervous system and the sensory feedback system, which can be divided into the visual, auditory, vestibular systems, and proprioception. These systems are critical for feedback control, which is an ongoing loop of acquisition and integration of sensory information that updates the current state and corrects posture accordingly in unperturbed and perturbed movements. These different feedback systems can decline independently and systems can also compensate for each other (Fig. 2) (Gadkaree et al., 2016).

Proprioceptive acuity
Proprioceptive feedback can come from muscle spindles, golgi tendon organs, and cutaneous and joint mechanoreceptors. There is an age-related reduction in the number of muscle spindles (Kararizou, Manta, Kalfakis, & Vassilopoulos, 2005). As a consequence, the joint position and motor sense deteriorates with age (about 3% per year between ages of 20 to 80 years for joint position) and affects motor tasks such as balance (Goble, Coxon, Wenderoth, Van Impe, & Swinnen, 2009). Joint position sense becomes more accurate through childhood and adolescence, peaks in young adulthood and then progressively deteriorates (Goble et al., 2009; Suetterlin & Sayer, 2013). Ageing also results in a

decreased number and density of cutaneous and joint mechanoreceptors (Lee, Kwon, Son, Nam, & Kim, 2013). This loss of sensation can be particularly impairing in the feet and hands, as the extremities are critical for movement and interaction with the environment. The most common experiments to test the proprioceptive acuity in humans are 1) position tests, in which participants replicate a joint position, 2) motion sense tests, in which participants need to detect motion of any of the limbs, and 3) dynamic position tests, in which position and motion sense tests are combined (Suetterlin & Sayer, 2013).

Visual acuity

Deterioration of vision due to ageing results in decrease of the visual acuity, decline in sensitivity of the visual field, decreased contrast sensitivity, and an increased dark adaptation threshold (Salvi, Akhtar, & Currie, 2006). Fear of falling and lack of balance have been associated with poor visual acuity (Aartolahti et al., 2013).   The influence of visual feedback on complex motor task performance is typically determined by performing the task with eyes opened and closed or comparing cohorts with poor visual acuity (Shin, An, & Yoo, 2018).

Hearing acuity

Although many adults retain good hearing as they age, hearing loss associated with ageing is common among elderly people (Liu & Yan, 2007). Hearing is influenced by genetics, environmental factors, such as exposure to loud noise, and intrinsic factors such as damage due to disease. Previous findings suggest that ambient sound and hearing have a significant influence on postural control and balance (Kanegaonkar, Amin, & Clarke, 2012).

Vestibular acuity

The vestibular system is responsible for an accurate perception of movement and self-orientation. Decline in the vestibular system results in balance deficits and can produce symptoms such as dizziness and a change in the control of head movements, for example in standing up (Tsutsumi et al., 2004). Specialized equipment can evaluate vestibular acuity, yet the measurable effect of the deterioration of the vestibular sensory end organs remains elusive (Zalewski, 2015). Nonetheless, inquiring of participants about any previous experienced balance losses or dizziness via a questionnaire could be beneficial for the interpretation of results in complex motor tasks (Duracinsky et al., 2007; Tamber, Wilhelmsen, & Strand, 2009).

Nervous system

In the central nervous system healthy ageing can result in gradual decline of cognitive processing, which can progress further through disease states such as dementia or step-wise following events such as a stroke. In either situation the ability of the brain to process and coordinate afferent information from neural circuits is impaired. This affects the ongoing loop of acquisition and integration of sensory information from the environment and movement planning. To quickly examine cognitive function, the Clock Drawing Test, embedded in several cognitive assessments, is a widely used reliable diagnostic test which is generally applicable as it is quick and easy to perform and has no educational or language barriers (Borson, Scanlan, Brush, Vitaliano, & Dokmak, 2000; Shulman, 2000; Shulman, Shedletsky, & Silver, 1986).

The age-related structural changes in the peripheral and the spinal level of the neural system , which is when sensory and motor neurons and interneurons located in the spinal cord are involved, can be quantified by the reduction in nerve conduction velocity (NCV), response amplitude, and the increase in motor and sensor noise. The NCV and response amplitude can be measured with a nerve conduction study (Frijns, Laman, Van Duijn, & Van Duijn, 1997; Palmieri, Ingersoll, & Hoffman, 2004; S. Sadeghi, Ghavanini, Ashraf, & Jafari, 2004). Ageing affects afferent nerves (from the muscle to the spine) more than the efferent nerves (Papegaaij, Taube, Baudry, Otten, & Hortobágyi, 2014; Scaglioni, Narici, Maffiuletti, Pensini, & Martin, 2003). However degeneration of efferent pathways is also evident, for example in the tibialis anterior muscle (McNeil, Doherty, Stashuk, & Rice, 2005).

Both in young and elderly, motor and sensor noise are apparent due to cellular noise, unfused twitches, or cross-talk between nerves (Faisal, Selen, & Wolpert, 2008). With ageing, motor and sensor noise increases, which introduces variability in the execution of a trial-to-trial motion. An estimate of motor and sensor noise has previously been determined in a motion capture lab by combining a theoretical feedback control model with experimental data on kinematics of participants in standing balance on a platform, subjected to external perturbations (Van Der Kooij & Peterka, 2011).
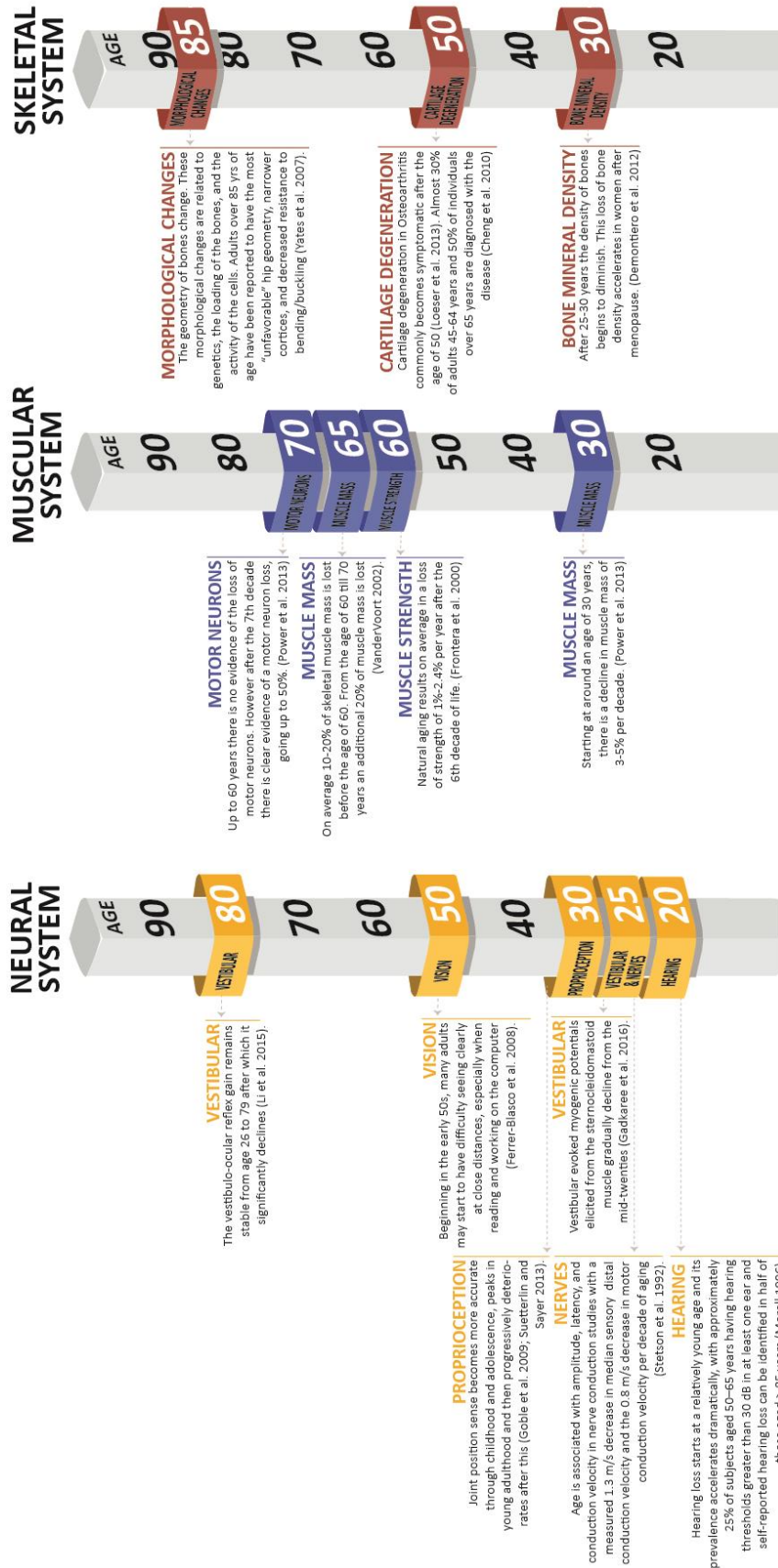
FIGURE 2: General onset of decline in the adult neural, muscular and skeletal system

3.1.2 Muscular capacity

Muscle strength and power reduces with age due to a reduction in muscle mass, reduced number of fast-twitch muscle fibres, slower contraction speed, and slower excitation-contraction decoupling (Mitchell et al., 2012) (Fig. 2). These reductions change the force-velocity relationship, resulting in shift of the normal curve to the left, due to decrease in contractile velocity at each relative load, and downward, due to loss of strength (Power, Dalton, & Rice, 2013; Vandervoort, 2002); The loss of skeletal muscle mass is site-specific and likely associated with the pattern of muscle activations that occurs in daily life activities. During exercise, the muscles that are being used have up-regulated hormone receptors that bind androgen, a group of hormones with declining age-related concentrations associated with sarcopenia (Morley, 2003).

Relative muscle thickness of the quadriceps and trunk muscles gradually decreases with age, and in men, arm, lower leg, and hamstrings muscle thickness reduces at old age (60-95 years) (Abe et al., 2011). Although the reduction in muscle thickness and associated muscle mass is associated with the decline in strength in older adults, muscle strength decline is more rapid than the loss of muscle mass, indicating that the quality of the muscle degrades (Goodpaster et al., 2006). This rate of strength decline also varies between muscle groups (Gross et al., 1998).

The effect of reduced muscle strength on motor tasks is the most widely studied factor of reserve. It is difficult to determine whether elderly people actually lack muscle strength or if they have other deficits that prevent them from performing the task (Gross et al., 1998; Hughes & Schenkman, 1996; Kotake, Miura, & Kajiwara, 1993). Different methods have been used to quantify muscle strength such as handgrip strength (Sallinen et al., 2010), induced muscle damage (e.g. 61), added weight (e.g. 43–45), or maximum isokinetic strength testing on a dynamometer.

Evaluating the maximum isometric (constant length contraction) or isokinetic (constant speed contraction) muscle strength (joint torque) of joints in relation to task performance can provide an indication of reserve in complex motor tasks. However, maximum voluntary joint torques are dependent on joint angle and angular velocity, due to the muscle force–length and force–velocity relationships. Directly predicting the (in)ability of complex motor tasks would therefore require a full angle-angular velocity torque profile of compensation strategies (D. E. Anderson, Madigan, & Nussbaum, 2007). Maximum voluntary contractions are also susceptible to large variability and are difficult to perform in impaired populations. Isolated strength tests therefore only partly reflect the actual strength available for a complex motor task.

Musculoskeletal modelling is an excellent tool to support the research in muscular reserve and movement strategies (Bajelan & Azghani, 2014; Bobbert, Houdijk, De Koning, & De Groot, 2002;

Caruthers et al., 2016). Where experimental studies have measurement limitations, modelling can complement measurements and observations with movement simulations to estimate individual muscle forces (Smith, Reilly, & Bull, 2019) .

3.1.3 Skeletal capacity

The human skeletal system is constantly adapting (Fig. 2). During development and ageing, bone shape responds to load and hormonal factors. Reshaping of the bone changes its functional abilities. Strength (stress to failure) is required to carry large loads, whereas toughness is required to absorb energy from an impact load. A proportional increase in tissue mineral content will generally yield stiffer (higher resistance to deformation) but more brittle bones (Boskey & Coleman, 2010). The effects combine so that with ageing, bones get stiffer, the cortices become thinner and toughness reduces, resulting in a greater likelihood of fracture. A common ageing disease is osteoporosis which results in more fragile bone and a greater risk of fragility fractures (Kanis, 2002).

The strength of bone is usually expressed by the bone mineral density (BMD). However, compared to young adults with the same BMD, the risk of fracture is still higher in elderly people as bone shape and quality is not captured by BMD (Kanis, 2002). Both cortical and trabecular bone becomes more brittle and weaker with age. Thus, it is the tissue-level properties in combination with the bone geometry that determine fracture risk. The most widely applied technique to measure bone mineral density is the dual energy x-ray absorptiometry (Shewale, Aglawe, Ambrose, Patta, & Choudhari, 2017).

Although the changed mechanics of bone at first sight do not directly translate to motor control of motor tasks, the consequences of change will affect movement. As the consequences of a fall are more severe (increased fracture risk), there is an increased fear of falling in the elderly, exacerbated by prior falls. This greater fear likely results in greater emphasis on stability as a movement objective in the motor control of movements (Fig. 1d). Furthermore, cartilage degeneration which is symptomatic in the disease Osteoarthritis (OA) results in pain with loading, and therefore puts more emphasis on pain avoidance. For example, the most prominent compensation strategy of unilateral knee and hip OA patients in standing-up is asymmetry of movement (compensation by selection) (Davidson et al., 2013; Eitzen, Fernandes, Nordsletten, Snyder-Mackler, & Risberg, 2014; Lamontagne, Beaulieu, Varin, & Beaulé, 2012; Naili, Broström, Gutierrez-farewik, & Schwartz, 2018; Turcot, Armand, Fritschy, Hoffmeyer, & Suvà, 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, Garn, Studies, & Rouge, 2013). Compensation by reorganisation is also apparent in knee OA patients in standing up where moderate knee OA patients try to maintain the same movement trajectory as healthy individuals, resulting in greater antagonist activation

(Bouchouras, Patsika, Hatzitaki, & Kellis, 2015; Davidson et al., 2013; Patsika, Kellis, & Amiridis, 2011). This greater activation most likely improves knee stability and provides relief from pain and discomfort.

Other factors relevant for analysis of age-related mobility limitations are changes in body mass distribution and reduced joint ranges of motion. The redistribution of body mass influences movement dynamics. A combination of muscle stiffness and skeletal changes results in a reduction of joint ranges of motion (ROM) with ageing. For example, the age-related reduced hip flexion range of motion approaches the maximal angle used in standing-up (Fotoohabadi, Tully, & Galea, 2010).

3.2 Compensation for Movement Objectives

Currently the scientific community is undecided on which combination of movement objectives (cost-functions) best reproduces movement strategies that older humans choose for motor tasks (Bobbert et al., 2002; A. Mughal & Iqbal, 2010; A. M. Mughal, Perviaz, & Iqbal, 2011; M. Sadeghi & Emadi, 2013). The central nervous system may even apply different weighting for different phases of a complex task (M. Sadeghi & Emadi, 2013). Movement objectives feed into our feedforward planning, which is a control system to anticipate and compensate for potential disturbances. A major limiting factor in this research area is the lack of a reliable independent quantitative measures of key known movement objectives including energy, stability, and pain.

3.2.1 Energy

Biomechanical studies generally assume, based on sensible analysis, that humans select their movement strategies via a continuous optimization of a cost function minimizing an energy objective (Todorov & Jordan, 2002). However, when performance is more important than energy efficiency (e.g., in sports), the relative weighting of movement objectives likely changes.

In gait there is evidence of age-related changes in weighting of movement objectives. It is well known that the relationship between oxygen consumption per unit distance and gait speeds is U-shaped, where the minimum of the curve matches the preferred walking speed in adults ("optimal walking speed") (di Prampero, 1986; Pearce et al., 1983). In older adults, however, preferred walking speed declines and energy expenditure per unit distance increases (Malatesta et al., 2003). Although walking effort in older adults increases overall due to biological changes (U-shape moves up), older adults also select a slower walking speed, which adds to the increased metabolic cost of transport. Thus, older adults no longer walk at the "optimal walking speed", but seem to have a shifted weighting in their movement objectives that results in a less energetically economic movement pattern (Malatesta et al., 2003).

Based on predictive neuromusculoskeletal modelling, the reason for this shift has been postulated to be minimisation of muscular fatigue rather than the minimisation of metabolic cost of transport (Song & Geyer, 2018). Although many factors of age-related capacity decline have been included in this study, possible psychological reasons have not been incorporated, such as an increased emphasis on stability or pain avoidance. Therefore, as not all confounding factors have not been taken into account, these studies cannot comment on the overall reasons for these changes.

A generally accepted measure of energy is estimation via measurement of oxygen uptake. Quantification of energy cost based on mechanics, and at the muscular level, however, is complex and the literature is undecided on the most appropriate method (van der Kruk, van der Helm, Veeger, & Schwab, 2018). The most commonly used models for metabolic cost in biomechanical modelling are Umberger et al. (2003), Bhargava et al. (2004), Lichtwark and Wilson (2005), and Houdijk et al. (2006).

3.2.2 Pain avoidance

The presence of pain substantially affects movement strategies and therefore it is important to incorporate a measure of pain. Pain avoidance can even lead to a long-term compensation, long after the pain is mitigated or eliminated (Farquhar, Reisman, & Snyder-Mackler, 2008). Former stressors or pain in participants might therefore still influence current movement strategies, which should be accounted for when analysing movement strategies. Pain assessments have scarcely been reported in experimental biomechanics literature. It could be quantified by the WOMAC pain questionnaire, or the Visual Analogue Scale (VAS), as pain currently cannot be measured directly (Linton & Boersma, 2003).

3.2.3 Stability

More severe consequences of injury and higher likelihood of falls increase the fear of falling in elderly people. A history of falls, lower levels of overall self-esteem, as well as flexibility and reduced knee strength are all predictors for fear of falling (Delbaere, Crombez, Vanderstraeten, Willems, & Cambier, 2004; Sales, Levinger, & Polman, 2017). Compensation due to fear of falling is a feedforward adjustment to reduce the likelihood of balance loss, which is apparent in elderly, fallers (elderly people with a history of falling), and in young adults in uncertain environments (Pavol & Pai, 2002). For example, in standing up, adults with a history of falls show different movement strategies compared to non-fallers regardless of their capacity, showing Compensation for Movement Objectives (Chen, Chang, & Chou, 2013; Chorin, Cornu, Beaune, Frère, & Rahmani, 2016). The Falls Efficacy Scale-International (FES-I) is a questionnaire to assess fear of falling in older people (Yardley et al., 2005).

3.2.4 Velocity

Elderly people can reduce the duration of their movements when asked to move as fast as possible and are therefore not bound to their initial self-selected speed (Vander Linden, Brunt, & McCulloch, 1994). Clear speed instructions are therefore critical and can help to understand the influence of this movement objective in relation to Compensation.

3.3 Experimental design: restricted compensation

Experimental design plays an important part in facilitating or constraining available compensation strategies. The design of an experiment is a trade-off between 1) standardization of the protocol to improve repeatability, robustness, and comparability and 2) replication of daily practice to allow for clinical and real-life translation. To take research on age-related limitations in standing-up as an example, most prior studies have typically used standardized experimental protocols, restricting compensation in their protocols (E. van der Kruk & Bull, 2019). For example, most studies on sit-to-stand do not permit the participants to compensate using their arms. This restriction poorly reflects the importance of arms in daily life, as more than half of the healthy elderly population is unable to stand up without the use of arms, and more than half of all adults prefer to use their arms when standing up (Komaris, Govind, Murphy, Ewen, & Riches, 2018; Mazzà, Benvenuti, Bimbi, & Stanhope, 2004). Such restricted experimental protocols facilitate comparison between groups and studies, but also limit their translation to characterising mobility of the elderly in their homes, communities, and clinic.

5. Conclusion

CaReMoOC provides a mean to communicate hypotheses and theories on movement impairments and limitations. CaReMoOC is a framework incorporating neuromuscular capacity (accumulation of NMSK resources over the lifespan), reserve (task-specific difference between capacity and task demand), movement objectives (considerations made to plan a movement), and compensation (use of NMSK resources to respond to the task demand).

With healthy ageing the NMSK capacity declines. This decline is apparent in the neural, muscular, and skeletal systems and each have their effect on the execution of complex motor tasks. For a specific task, humans have NMSK reserve, so that, if NMSK capacity reduces, the task is not necessarily impaired. Moreover, humans have multiple compensation strategies to meet the task goal. These compensation strategies can be based on changed movement trajectories (selection) or enhanced muscle recruitment (reorganization). There are two cases of compensation; Compensation for

capacity, when capacity does not meet the task demands, or Compensation for Movement Objectives, due to psychological reasons.

To predict movement limitations, we need to find ways to quantify NMSK reserve. This requires reliable means to measure and estimate NMSK capacity (muscular, neural skeletal) and task demand. Moreover, this requires validation of the completion and reliability of the optimal control theory for movement impairments. This starts with incorporating existing psychological measures of movement objectives in biomechanical and motor control research (e.g. FES-I, VAS), but also requires development of novel reliable diagnostic tools and models for pain, stability (Bruijn, Meijer, Beek, & Van Dieën, 2013), and energetics. Finally, experimental design should allow for more realistic compensation strategies by removing constraints on postural behaviour.

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List of Abbreviations

BMD		Bone Mineral Density
CaReMoOC		Referring to the framework of Capacity, Reserve, Movement Objectives, and Compensation
FES-I		Falls Efficacy Scale-International questionnaire
NMSK		Neuromusculoskeletal
OA		Osteoarthritis
ROM		Range of Motion
VAS		Visual Analogue Scale

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