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Sex-dependent and sex-independent muscle activation patterns in adult gait as a function of age

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ABSTRACT

Introduction: Aging leads to poorer neuromuscular control that may impact mobility. However, the specific decades when these changes occur, and whether these time-based changes are sex-specific, are unclear.
Methods: Adults aged 20–82 years (N = 93, 51 females) walked six gait trials at their preferred speed over a 10-m platform. Electromyography (EMG) of the rectus femoris (RF), tibialis anterior (TA), and gastrocnemius lateralis (GL) were measured using wireless surface sensors. Root mean square (RMS) and within-cycle coefficient of variation (CV) values were calculated for several phases of gait. Mixed effect models were conducted to test for Age, Sex, Muscle, and interaction effects, covarying for gait speed and stride length.
Results: A significant Age × Sex × Muscle interaction on RMS at the mid-swing phase was found ($p = .036$), showing 4.2% higher RF RMS for males ($\beta = 0.42$, $p = .008$) and 3.3% higher GL RMS for females ($\beta = 0.33$, $p = .038$) with each of the three decades investigated. Significant Age × Muscle interactions on GL RMS were found at loading, mid-stance, and over the full gait cycle ($ps < .05$), with 2.0–4.3% higher values per decade ($\beta = 0.20$–0.43, $ps < .05$). There was generally higher CV with higher age at mid-swing and over the full gait cycle (significant Age effects, $ps < .05$). Females showed higher CV at loading, mid-stance, and terminal stance (significant Age × Sex effects, $ps < .05$).
Discussion/conclusion: Results suggest sex-dependent influences of age on muscle recruitment during a few specific phases of gait, and sex-independent influences of age on the recruitment of the ankle musculature, and on the overall gait cycle. These influences may help explain overall increased instability and fall risk in older adults.

1. Introduction

Normal aging is a gradual process that impacts strength and gait stability. Each year after 40 years of age, adults may lose as much as 1.5% of their maximal strength (Vandervoort, 2002). Strength deficits are also present during dynamic contractions (Vandervoort, 2002; Deschenes, 2004; Kirkendall and Garrett, 1998), such as those during gait. These decreases in strength can have functional consequences. For instance, lower limb strength is correlated to gait stability (Moxley Scarborough et al., 1999) and is predictive of falls (Pijnappels et al., 2008), which lead to some of the most common injuries suffered by older adults. One consequence of falls can be functional dependence, which has also been shown to be independently associated to gait function (Gill et al., 1995). Although gait function seems to be directly linked to age-related changes in lower limb strength, older adults remain more unstable than young adults after controlling for strength, suggesting that other physiological changes have a role in age-related gait instability (Kang and Dingwell, 2008).

Age-related differences in mobility and fall risk occur alongside other changes in gait patterns. Generally, older adults have slower preferred gait speeds than young adults (Smith et al., 2002; Ko et al., 2011; Kobayashi et al., 2016) and longer stance and double-support durations (Beauchet et al., 2017), which together could be interpreted as reflecting age-related adaptation strategies to optimize gait stability. Moreover, DeVita and Hortobagyi (2000) found that older adults have higher hip extensor torque and power, and lower ankle plantar flexor

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torque and power compared to younger adults, and interpreted this as a redistribution of joint loads from the ankle to the hip due to joint-specific effects of aging on musculoskeletal structures of these joints.

The previously observed age-related redistribution of joint torque and power at the ankle and hip suggests that there may be changes in how muscles are recruited during gait. Schmitz et al. (2009) explored these muscle activations during the gait cycle using electromyography (EMG), and found that older adults had higher normalized muscle activation than young adults at preferred speed, citing differences at the gastrocnemius lateralis (GL) during loading, and at the vastus lateralis, soleus, tibialis anterior (TA), and rectus femoris (RF) during mid-stance. While higher RF and vastus lateralis activation may be expected in an ankle-to-hip change in joint loading, the higher TA, soleus and GL are not, and could instead be interpreted as higher co-activation during gait, a common stabilizing feature of older adults (Hortobágyi and Devita, 2006; Hortobágyi et al., 2009) that could result in both higher ankle joint stiffness and lower ankle joint power. Schmitz et al. (2009) concluded that the age effect was more prominent for uniarticular than biarticular muscles; however, this conclusion was based on a comparison of the soleus and GL at mid-stance in a fast gait speed condition, and may not reflect observations across all phases during preferred speed gait. In fact, the age effect on soleus activation during mid-stance was smaller in magnitude than the age effect on GL activation during loading (Schmitz et al., 2009), meaning biarticular muscles could see larger age-related changes at preferred speed gait. Marques et al. (2016) also observed a higher TA activation during stance in older adults, however, they also found lower RF activation, contrasting with Schmitz et al. (2009). Since the study from Marques et al. (2016) assessed only females, this suggests that sex may be an influencing factor in the effect of age on gait muscle activity.

Indeed, an individual's sex seems to affect their motion and joint loading during gait. While some studies of young and old adults have found that females walk at a slower preferred speed than males (Callisaya et al., 2010; B.L. Cho et al., 2004), the majority report equal gait speeds (Smith et al., 2002; Ko et al., 2011; Kobayashi et al., 2016; Mengarelli et al., 2017; Di Nardo et al., 2015; Kerrigan et al., 1998; Bruening et al., 2015) with shorter stride lengths (Smith et al., 2002; Ko et al., 2011; Kobayashi et al., 2016; Kerrigan et al., 1998; Bruening et al., 2015) and higher cadences (Smith et al., 2002; Ko et al., 2011; Kobayashi et al., 2016; Mengarelli et al., 2017; Di Nardo et al., 2015; Kerrigan et al., 1998; Frimenko et al., 2015). These shorter and faster strides for females, once factoring in sex differences in height, occur with proportionally larger hip, knee, and ankle range of motion during the gait cycle (Ko et al., 2011; Røislien et al., 2009), and with less positive work performed by the knee and more negative work performed by the hip and knee (Ko et al., 2011). This seems to show that sex, like age, could also affect joint load distribution during gait. At mid-stance, for instance, lower knee and ankle joint loads were found in females compared to males, independent of height and mass (S.H. Cho et al., 2004). At terminal stance, however, females have higher magnitudes and longer durations of knee flexion and ankle plantar flexion (Ko et al., 2011; Kerrigan et al., 1998; Røislien et al., 2009), as well as higher knee extension torque (S.H. Cho et al., 2004), suggesting that females transition from double to single-leg stance with more motion amplitude than males. Moreover, sex differences in gait kinematics can be age-dependent (Kobayashi et al., 2016). Ko et al. (2011) reported that the duration of ankle dorsiflexion during initial swing increased with age more steeply for females than for males, meaning that sex may affect the age-related changes in ankle motion. With epidemiological evidence that falls occur more frequently and are more serious in older females than in older males (O'Loughlin et al., 1993; Stevens and Sogolow, 2005), an investigation of how sex affects age-related changes in gait motion is needed.

These sex-dependent changes in knee and ankle motion and loading are likely due in part to sex differences in muscle recruitment. Young female adults tend to activate their TA and GL to a greater extent than males within a single gait stride (Di Nardo et al., 2015), which the authors suggest demonstrates a more complex gait activation pattern for females. Moreover, this same group recently demonstrated that this sex difference in TA and GL activation profile was absent in children aged 6–8 but appeared in those aged 10–12, where sex-related motor control features may start to appear (Di Nardo et al., 2017). However, while sex seems to influence the shape of EMG in gait in young adults, little is known about its influence in older adults.

Further, the experimental design of previous muscle activation studies can limit the interpretation of the “age” effect. A statistical approach that groups participants into a young group and an older group (Schmitz et al., 2009; Marques et al., 2016; Theou et al., 2013) has typically been used, although age itself is a continuous measure. The older groups in these studies had a mean age > 70 years (Schmitz et al., 2009; Theou et al., 2013), limiting the interpretation of the “age” effect to adults > 70 years, or an age range > 20 years (Marques et al., 2016), requiring an assumption that older adults at the top (82 years) and bottom (60 years) of the range respond with the same “age” effect. Using regression models that treat age as a continuous variable, and/or more than a single group of older adults may more robustly capture the effects of aging and provide an estimate of the amount of change associated with the aging process.

To our knowledge, no study has assessed the effects of older age as a continuous variable on gait muscle activation separately for males and females. Therefore, the objective of this study was to assess the interaction between age and sex on lower limb muscle activation during gait. Since Ko et al. (2011) reported an Age × Sex interaction on duration of ankle dorsiflexion, we hypothesized that aging would affect TA and GL activation differently for males and females. We also hypothesized that, due to a belief that females have more complex activation of lower limb muscles during gait (Di Nardo et al., 2015), females would have more variable EMG signal shapes than males, regardless of age.

2. Methods

2.1. Participants

From 2014 to 2017, 93 healthy adults aged 20 years and over were recruited among students and staff of University of Cagliari (Italy) and among people attending the University of the Third Age of Quartu S. Elena (Italy) on a voluntary basis. Participants were recruited following group meetings that detailed the purposes of the study and the experimental procedures. An exclusion criterion was the existence of any neurologic or orthopedic condition severely impairing gait, balance and muscular strength. A physician was consulted to examine borderline cases. Participants provided informed consent to participate in this study, which was given ethics clearance from the institutional ethics board.

2.2. Gait analysis

Upon arrival, participants were instrumented for EMG gait analysis. EMG data were collected using wireless surface bipolar electrode sensors (FreeEMG, BTS Bioengineering, Italy) that sampled at 1000 Hz. Sensor dimensions were 41.5 × 24.8 × 14 mm and 17 × 8 mm for the mother and satellite sensors, each containing 17 mm electrodes that were placed at an interelectrode distance of 20 mm (gain: 1065.4; range ± 1.5 mV; input impedance: > 10 GΩ; CMRR: > 110 dB at 50–60 Hz). Using SENIAM guidelines for the lower limb (Hermens et al., 2000), the RF sensor was placed halfway on the line between the anterior superior iliac spine and the superior aspect of the patella, the TA sensor was placed one third of the distance from the fibular head on the line to the medial malleolus, and the GL sensor was placed one third of the distance from the fibular head on the line to the heel. These muscles were selected due to contrasting results on the effect of age on