Gait & Posture 73 (2019) 315–322

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Knee muscle co-contractions are greater in old compared to young adults during walking and stair use

Vishnu D. Chandran[a], Jan A. Calalo[a], Philippe C. Dixon[b,c], Jack T. Dennerlein[b,d], Jeffrey M. Schiffman[c], Saikat Pal[a,*]

[a] Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, NJ, United States
[b] Department of Environmental Health, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, United States
[c] Liberty Mutual Research Institute for Safety, Boston, MA, United States
[d] Bouvé College of Health Sciences, Northeastern University, Boston, MA, United States

ARTICLE INFO

Keywords:
Muscle co-activation
EMG
Gait
Stair ascent
Stair descent

ABSTRACT

Background: Muscle co-contraction is an accepted clinical measure to quantify the effects of aging on neuromuscular control and movement efficiency. However, evidence of increased muscle co-contraction in old compared to young adults remains inconclusive.
Research Question: Are there differences in lower-limb agonist/antagonist muscle co-contractions in young and old adults, and males and females, during walking and stair use?
Methods: In a retrospective study, we analyzed data from 20 healthy young and 19 healthy old adults during walking, stair ascent, and stair descent at self-selected speeds, including marker trajectories, ground reaction force, and electromyography activity. We calculated muscle co-contraction at the knee (vastus lateralis vs. biceps femoris) and ankle (tibialis anterior vs. medial gastrocnemius) using the ratio of the common area under a muscle pairs' filtered and normalized electromyography curves to the sum of the areas under each muscle in that pair.
Results: Old compared to young adults displayed 18%–22% greater knee muscle co-contractions during the entire cycle of stair use activities. We found greater (17%–29%) knee muscle co-contractions in old compared to young adults during the swing phase of walking and stair use. We found no difference in ankle muscle co-contractions between the two age groups during all three activities. We found no difference in muscle co-contraction between males and females at the knee and ankle joints for all three activities.
Significance: Based on our findings, we recommend clinical evaluation to quantify the effects of aging through muscle co-contraction to include the knee joint during dynamic activities like walking and stair use, and independent evaluation of the stance and swing phases.

1. Introduction

Muscle co-contraction, defined as the simultaneous contraction of an agonist and antagonist muscle pair crossing a joint, is a measure of motor control [1]. Muscle co-contraction is theorized to provide movement accuracy, energy efficiency, and adaptation to environmental demands [2]. Muscle co-contraction is reported to maintain joint integrity during ballistic movements, protecting ligaments from excessive forces during rapid acceleration and deceleration of bones [3,4]. Changes in muscle co-contraction are associated with degradation of motor control, and have been associated with aging, stroke, cerebral palsy, Parkinson's disease, and joint replacement [5,6]. In understanding the effects of aging on motor control, it is accepted that the execution of activities of daily living such as walking, stair ascent, and stair descent require substantially greater effort in old compared to young adults relative to their available maximal capacity [7]. One theorized cause for this greater effort in old compared to young adults is increased muscle co-contraction, which acts as an evolving functional mechanism [7] to counter the loss of balance [8], stability [9], and sensory processing [10] with aging. The increased muscle co-contraction leads to increased joint stiffening [10], greater compressive forces, and increased metabolic cost [11]. Although muscle co-contraction is an accepted clinical measure to study the effects of aging on motor control [12,13], evidence of increased muscle co-contraction in old

* Corresponding author at: Department of Biomedical Engineering, New Jersey Institute of Technology, 111 Lock Street, Room 106, Newark, NJ 07102, United States.
E-mail address: pal@njit.edu (S. Pal).

https://doi.org/10.1016/j.gaitpost.2019.07.501
Received 16 April 2019; Received in revised form 8 July 2019; Accepted 31 July 2019

compared to young adults remains inconclusive.

There is a lack of clarity and depth in the literature regarding increased muscle co-contraction in old compared to young adults during walking and stair use. During level walking trials, studies have reported higher muscle co-contraction in old compared to young adults at the knee and ankle joints [14,15], at the knee joint with no differences at the ankle [11], at the ankle joint with no differences at the knee [16], at the knee joint with the ankle not evaluated [17], and at the ankle joint with the knee not evaluated [18]. Next, stair ascent and descent are more demanding tasks than level walking, but evidence in support of increased muscle co-contraction in old compared to young adults during stair ascent and descent is sparse. To the best of our knowledge, only two studies have compared muscle co-contraction in healthy young and old adults during stair ascent and descent activities [7,19]. Both these studies reported higher muscle co-contraction in old compared to young adults at the knee joint [7,19]; Hortobagyi et al. did not evaluate muscle co-contractions at the ankle joint [7], while Larsen et al. did not find any differences at the ankle joint [19]. The lack of consensus in studies during walking, and limited data during stair ascent and descent, make it difficult to extract clinical relevance from existing literature.

In addition to age-related differences, gender differences in muscle co-contraction during walking and stair use remain unclear. To the best of our knowledge, only one study has compared muscle co-contraction in healthy males and females during walking [20]. Mengarelli et al. reported consistently greater muscle co-contraction in females compared to males at the ankle joint [20]. It is unclear, however, if gender differences in muscle co-contraction exist at the knee joint, and during stair ascent and stair descent activities.

Accordingly, the goal of this study was to determine if there were differences in lower-limb agonist and antagonist muscle co-contraction in healthy young and old adults, and in males and females, during walking and stair use. Specifically, we addressed the following research questions: 1) are muscle co-contractions at the knee and ankle joints greater in old compared to young adults during walking, stair ascent, and stair descent?, 2) is muscle co-contraction associated with age?, and 3) are there gender differences in muscle co-contractions at the knee and ankle joints during walking, stair ascent, and descent activities? We hypothesized that 1) muscle co-contractions at the knee and ankle joints are greater in old compared to young adults during walking, stair ascent, and stair descent activities, 2) muscle co-contractions are associated with age, and 3) muscle co-contractions at the knee and ankle joints are greater in females compared to males during walking, stair ascent, and stair descent activities.

2. Methods

2.1. Participant recruitment

We recruited 39 healthy participants for this study, 20 young (11 males, 9 females) and 19 old (9 males, 10 females) adults (Table 1). The young adults were taller than the old adults for the gender-combined and gender-specific age groups (Table 1, two-tailed, unpaired t-tests). Males weighed more than females in both age groups (Table 1, two-tailed, unpaired t-tests). There was no difference in exercise time between the young and old adults for the gender-combined or gender-specific age groups (Table 1, two-tailed, unpaired t-tests). We screened the participants for current or history of neurological or musculoskeletal deficits that might affect their mobility, and uncorrectable visual impairment or vestibular dysfunction. Prior to participation, each participant was informed on all aspects of the study and provided signed consent according to the policies of an Institutional Review Board.

2.2. Gait and electromyography measurements

We analyzed each participant during walking, stair ascent, and stair descent activities at self-selected speeds [21], with simultaneous measurements of three-dimensional marker trajectories, ground reaction force, and muscle electromyography (EMG) activity (Fig. 1). A 12-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) was used to analyze lower extremity motion. Twenty nine retro-reflective markers were placed on bony landmarks based on previously established marker sets [22,23]. Retro-reflective marker trajectories were sampled at 60 Hz, reconstructed and filtered using a low-pass, fourth-order Butterworth filter with a cutoff frequency of 8 Hz [21]. Ground reaction force was measured using embedded force plates (Kistler Instrument Corp., Amherst, NY). The participants performed all activities with bare feet. During walking trials, a participant traversed a level walkway embedded with four force plates. During stair ascent/decent trials, a participant traversed a four-step wooden staircase embedded with three force plates, with four force plates at the bottom of the staircase (Fig. 1A). The wooden staircase had a riser height of 17 cm, depth of 28 cm, and width of 90 cm per step. The staircase had handrails on each side for safety (Fig. 1A). The handrails were 90 cm high with 5 cm circular diameter. We instructed the participants to walk in a step-over manner, with one foot contact per stair, on the staircase without using the handrails [21]. During stair ascent, a participant walked on level ground for 3 m prior to stepping onto the staircase, ascended the four steps, and walked to the end of a 2.5-meter elevated walkway. During stair descent, a participant walked the 2.5-meter elevated walkway, descended the four steps, and walked on the 3-meter level ground. Ground reaction force data were sampled at 1020 Hz. A minimum of three successful trials, defined as all foot placements entirely on single force plates during an activity, was a criterion for a participant to be included in this analysis. Based on this criterion, nine, two, and one participants were excluded from walking, stair ascent, and stair descent analyses, respectively. Although we collected data from both legs, only one leg per participant (the leg with the greater number of successful trials) was included in this study. Spatiotemporal gait parameters, including walking, stair ascent, and stair descent speeds and stride lengths were calculated from marker trajectories.

We measured muscle activation during walking, stair ascent, and stair descent trials using a multi-channel surface EMG system (Trigno™, Delsys Inc., Natick, MA). Electromyography data were sampled at 1020 Hz for all three activities. We recorded EMG measurements from the vastus lateralis, biceps femoris, tibialis anterior, and medial gastrocnemius muscles according to established guidelines [24,25]. Prior to the functional trials, resting EMG signals were recorded with a participant stationary and relaxed. We subtracted a participant's mean resting EMG value from his/her raw EMG from functional trials to offset the functional trial data to zero. The EMG data were then filtered using a second order Butterworth bandpass filter (20–500 Hz) to remove motion artifact, full-wave rectified, and again filtered with a fourth order 10 Hz Butterworth low-pass filter [15,26]. The filtered EMG data were dynamically normalized to muscle-specific maximum activations obtained from all successful trials of walking, stair ascent, and stair descent for each participant [27,28]. In other words, EMG data from each muscle were normalized to the maximum value over all successful trials of all three activities. To clarify, we did not use isometric contraction to normalize our EMG data. We synchronized the EMG signals with the marker and vertical ground reaction force data to label the stance and swing phases of an activity (Fig. 1B and C). Heel strike, the beginning of stance phase, was labeled as the frame with the first non-zero value of vertical ground reaction force. Toe off, the end of stance and beginning of the swing phase, was labeled as the frame with the first zero value of vertical ground reaction force. For walking trials, the second heel strike marking the end of the swing phase was determined by visual inspection of the heel markers as the heels came in contact with the ground; this qualitative method was used because we did not have force plates to record the second heel strike during walking trials.

Table 1
Population characteristics of the young and old participants recruited for this study. The *p* values were from two-tailed, unpaired t-tests between the groups.

All participants	Young (n = 20)			Old (n = 19)			*p* value
	Mean	SD	Range	Mean	SD	Range	
Age (years)	25.7	4.9	18.0 – 35.0	74.4	6.0	66.0 – 87.0	
Height (meters)	1.72	0.09	1.54 – 1.86	1.62	0.08	1.51 – 1.77	< 0.001
Weight (kgs)	71.1	10.7	48.5 – 89.0	71.4	17.8	50.5 – 117.0	0.946
Exercise time per week (hours)	3.0	2.1	0.0 – 7.0	2.8	1.7	0.0 – 5.0	0.862
Young adults	**Males (n = 11)**			**Females (n = 9)**			***p* value**
	Mean	SD	Range	Mean	SD	Range	
Age (years)	25.3	5.8	18.0 – 35.0	26.2	3.8	22.0 – 33.0	0.678
Height (meters)	1.78	0.06	1.71 – 1.86	1.66	0.07	1.54 – 1.76	< 0.001
Weight (kgs)	76.4	9.0	62.3 – 89.0	64.6	9.9	48.5 – 81.0	0.010
Exercise time per week (hours)	2.7	2.4	0.0 – 7.0	3.2	1.8	1.0 – 6.0	0.616
Old adults	**Males (n = 9)**			**Females (n = 10)**			***p* value**
	Mean	SD	Range	Mean	SD	Range	
Age (years)	72.3	5.0	67.0 – 80.0	76.2	6.5	66.0 – 87.0	0.167
Height (meters)	1.70	0.04	1.64 – 1.77	1.55	0.04	1.51 – 1.64	< 0.001
Weight (kgs)	84.8	15.7	59.3 – 117.0	59.3	8.6	50.5 – 76.0	< 0.001
Exercise time per week (hours)	2.7	2.1	0.0 – 5.0	3.0	1.4	0.0 – 4.0	0.683

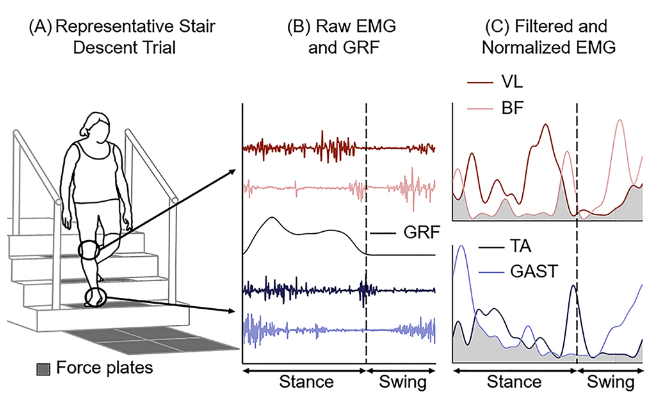

Fig. 1. Measurement of muscle co-contraction at the knee and ankle joints during (A) a representative stair descent trial. Raw (B) and filtered and normalized (C) electromyography (EMG) activations of the vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), and medial gastrocnemius (GAST) muscles were synchronized with vertical ground reaction force (GRF) data to label the stance and swing phases. The shaded regions in (C) are the common areas between the muscle pairs. The ratio of the common area of a muscle pair to the sum of the areas under each muscle in that pair represents co-contraction at that joint.

2.3. Muscle Co-contraction analysis

We calculated muscle co-contraction at the knee and ankle joints for all successful trials of walking, stair ascent, and stair descent activities (Fig. 1). We used an established method for calculating muscle co-contraction [1,26,29], given by:

$$\text{Percent muscle co-contraction} = 2*\frac{\text{Common area A \& B}}{\text{Area A} + \text{Area B}}*100 \quad (1)$$

where A and B were filtered and normalized EMG curves of an agonist/antagonist muscle pair crossing a joint. Area A was the area under the EMG curve of muscle A, Area B was the area under the EMG curve of muscle B, and the common area A & B was the intersection of the EMG curves of muscles A & B. Muscle co-contraction at the knee joint was evaluated between the vastus lateralis and biceps femoris muscles [11,14,17], while muscle co-contraction at the ankle joint was evaluated between the tibialis anterior and gastrocnemius muscles [11,14,16,20,26]. Muscle co-contraction values from individual trials of an activity were averaged for each participant. We calculated muscle co-contraction from the entire cycle of an activity, and from further classification of an activity into its stance and swing phases.

2.4. Data analysis and statistical methods

We compared average muscle co-contraction from young and old adults during walking, stair ascent, and stair descent activities at the knee and ankle joints. We compared average muscle co-contraction from the entire cycle of an activity, and from the stance and swing phases of each activity. We chose $p < 0.050$ for testing significance between the groups and then corrected for multiple comparisons using Bonferroni correction. Our data failed the normality test, and as such, significant differences between the groups were evaluated with the one-tailed Mann Whitney test (post-Bonferroni correction, $p < 0.017$ for the entire cycle of the three activities; $p < 0.025$ for the stance and swing phases of each activity). Next, we evaluated the relationship between age and muscle co-contraction in young and old adults. Linear regression models were used to test for the significance of a relationship ($p < 0.050$). Finally, we compared average muscle co-contraction from males and females during walking, stair ascent, and stair descent activities at the knee and ankle joints using the two-tailed Mann Whitney test (post-Bonferroni correction, $p < 0.017$ for the entire cycle of the three activities; $p < 0.025$ for the stance and swing phases of each activity).

3. Results

Old adults displayed greater muscle co-contraction at the knee joint during the entire cycle of stair ascent and descent activities compared to young adults (Fig. 2). Average knee muscle co-contractions were 22% and 18% greater in old compared to young adults during the entire cycle of the stair ascent ($p = 0.002$) and stair descent ($p < 0.001$),

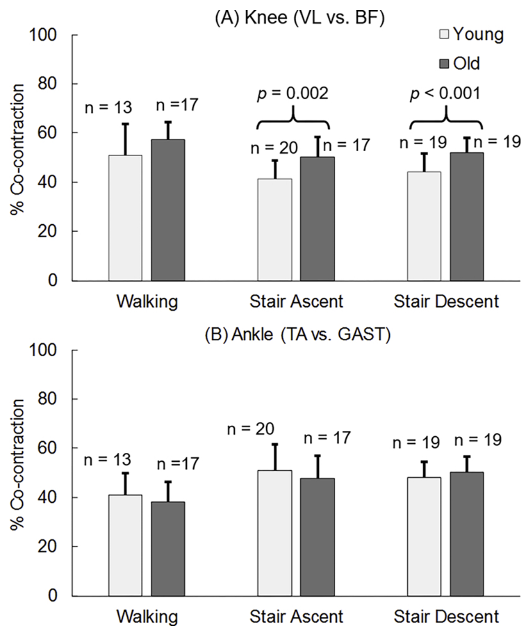

Fig. 2. Average (+1 SD) muscle co-contractions for young and old adults during walking, stair ascent, and stair descent activities evaluated at the (A) knee and (B) ankle joints. Average muscle co-contractions from the entire cycle (stance and swing) of the three activities are shown. At the knee joint, muscle co-contraction was evaluated from the vastus lateralis (VL) and biceps femoris (BF) muscles. At the ankle joint, muscle co-contraction was evaluated from the tibialis anterior (TA) and medial gastrocnemius (GAST) muscles. The number of participants in each group are shown next to the bars. *p* values are shown for the statistically significant differences ($p < 0.017$ post-Bonferroni correction).

respectively (Fig. 2A). Average knee muscle co-contractions were similar for the two age groups during the entire cycle of walking ($p = 0.084$, Fig. 2A). At the ankle joint, average muscle co-contractions were similar for the two age groups during the entire cycle of walking ($p = 0.238$), stair ascent ($p = 0.237$), and stair descent ($p = 0.215$) activities (Fig. 2B).

Evaluating muscle co-contractions independently during the stance and swing phases of each activity, old compared to young adults displayed consistently greater knee muscle co-contraction during the swing phase (Fig. 3). Average knee muscle co-contractions during the swing phase were 26%, 29%, and 17% greater in old compared to young adults during walking ($p = 0.016$, Fig. 3A), stair ascent ($p = 0.011$, Fig. 3B), and stair descent ($p = 0.013$, Fig. 3C) activities, respectively. During the stance phase, average knee muscle co-contraction was 21% greater in old compared to young adults during stair ascent ($p = 0.008$, Fig. 3B); these differences were close to significance during stair descent (13% greater in old adults, $p = 0.025$, Fig. 3C). Average muscle co-contractions were similar for the two age groups during the stance phase of walking ($p = 0.467$, Fig. 3A). At the ankle joint, we found no difference in muscle co-contraction between the two age groups during the stance ($p = 0.179$) and swing ($p = 0.417$) phases of walking (Fig. 3D), the stance ($p = 0.176$) and swing ($p = 0.140$) phases of stair ascent (Fig. 3E), and the stance ($p = 0.320$) and swing ($p = 0.270$) phases of stair descent (Fig. 3F).

Muscle co-contraction was associated with age only at the ankle joint in old adults during stair descent ($R^2 = 0.43$, $p = 0.002$, Fig. 4L). At the knee joint, this relationship between age and muscle co-contraction was close to significance in old adults during stair descent ($R^2 = 0.20$, $p = 0.057$, Fig. 4J). We found no relationship between age and muscle co-contraction in young adults during stair descent evaluated at the knee ($R^2 = 0.004$, $p = 0.808$, Fig. 4I) or the ankle ($R^2 = 0.10$, $p = 0.182$, Fig. 4K) joint. We found no relationship between age and muscle co-contraction during walking (Fig. 4A–D) and stair ascent (Fig. 4E–H) at the knee and ankle joints.

We found no difference in muscle co-contraction between males and females (Fig. 5). At the knee joint, average muscle co-contractions were similar for the two gender groups during the entire cycle of walking ($p = 0.493$), stair ascent ($p = 0.403$), and stair descent ($p = 0.075$) activities (Fig. 5A). At the ankle joint, average muscle co-contractions were similar for the two gender groups during the entire cycle of walking ($p = 0.493$), stair ascent ($p = 0.553$), and stair descent ($p = 0.070$) activities (Fig. 5B). We found no difference in muscle co-contraction between males and females during the stance and swing phases of all three activities (figures not shown).

We found no association between muscle co-contraction and activity speed. Young adults recorded greater speeds during all three activities compared to the old adults. During walking, average ± SD speeds for young and old adults were 1.31 ± 0.10 and 1.21 ± 0.13, respectively ($p = 0.008$). During stair ascent, average ± SD speeds for young and old adults were 0.80 ± 0.08 and 0.73 ± 0.11, respectively ($p = 0.013$). During stair descent, average ± SD speeds for young and old adults were 0.74 ± 0.10 and 0.61 ± 0.10, respectively ($p < 0.001$).

4. Discussion

The purpose of this study was to determine if there were differences in lower-limb agonist and antagonist muscle co-contractions in healthy young and old adults, and in males and females during walking and stair use. We sought to answer three research questions. Our first research question was: are muscle co-contractions at the knee and ankle joints greater in old compared to young adults during walking, stair ascent, and stair descent? Our results showed 18%–22% greater muscle co-contractions at the knee joint in old compared to young adults from the entire cycle of stair ascent and descent activities (Fig. 2A). We found greater (17%–29%) knee muscle co-contraction in old compared to young adults during the swing phase of walking, stair ascent, and stair descent (Fig. 3A). We found no difference in muscle co-contraction at the ankle joint during all three activities (Figs. 2B, 3 D–F). Our second research question was: is muscle co-contraction associated with age? Our results showed an association between muscle co-contraction and age only at the ankle joint in old adults during stair descent (Fig. 4). Our third research question was: are there gender differences in muscle co-contraction at the knee and ankle joints during walking, stair ascent, and descent activities? We found no difference in muscle co-contraction at the knee and ankle joints in males and females during walking, stair ascent, and stair descent activities (Fig. 5).

To the best of our knowledge, this is the first study to evaluate simultaneously muscle co-contractions at the knee and ankle joints during walking, stair ascent, and stair descent activities. Our results demonstrate greater muscle co-contraction in old compared to young adults only at the knee joint (Figs. 2 and 3). A possible explanation is that old adults demonstrate greater hip flexion (leaning forward) compared to young adults during activities of daily living, requiring larger hip extensor moments and hamstring activity [7]. With all other study variables remaining constant, we found no differences in muscle co-contraction between the two age groups at the ankle joint during walking, stair ascent, and stair descent. These results corroborate the findings of a previous study evaluating muscle co-contraction in young and old adults during stair ascent and descent [19], but contradict previous walking studies that reported greater muscle co-contractions at the ankle joint of old compared to young adults [14–16,18]. These contradictions may be explained, in part, due to differences in the study methods. Hortobagyi et al. 2009 used a different method to calculate muscle co-contraction, measuring timing and amplitude of antagonist muscle pairs [14]. Nagai et al. used a different muscle pair (tibialis anterior vs. soleus) to calculate muscle co-contraction at the ankle [18]. Hallal et al. [15] and Franz and Kram [16] conducted their walking trials on a treadmill, while our participants walked overground.

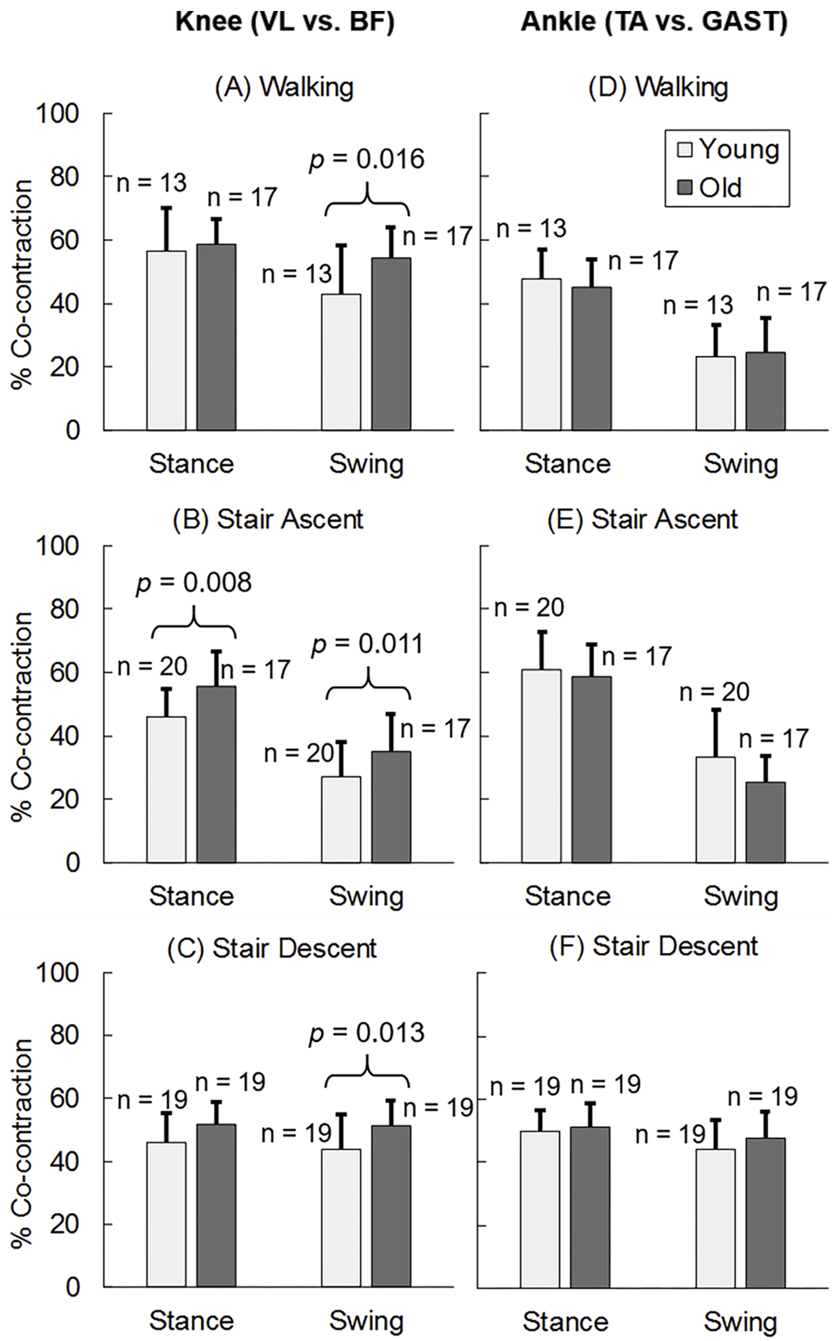

Fig. 3. Average (+1 SD) muscle co-contractions for young and old adults during the stance and swing phases of (A, D) walking, (B, E) stair ascent, and (C, F) stair descent activities evaluated at the (A, B, C) knee and (D, E, F) ankle joints. At the knee joint, muscle co-contraction was evaluated from the vastus lateralis (VL) and biceps femoris (BF) muscles. At the ankle joint, muscle co-contraction was evaluated from the tibialis anterior (TA) and medial gastrocnemius (GAST) muscles. The number of participants in each group are shown next to the bars. *p* values are shown for the statistically significant differences ($p < 0.025$ post-Bonferroni correction). The difference between the means was close to significance ($p = 0.025$) at the knee joint during the stance phase of stair descent (C).

Another possible reason may be that similar exercise levels in the old and young adults in our study ($p = 0.862$) minimized the increases in muscle co-contraction observed at the ankle joint in previous old adult cohorts.

Old adults displayed greater knee muscle co-contractions compared to young adults during the swing phase of walking, stair ascent, and stair descent (Fig. 3). Lo et al. concluded that “the stance and swing phases of the gait cycle should be considered independently when measuring lower limb muscle co-contraction during walking” [26]. Indeed, we found no difference in knee muscle co-contraction between the two age groups from the entire cycle of walking (Fig. 2A); however, considering the stance and swing phases independently, old adults demonstrated greater knee muscle co-contraction during the swing phase of walking (Fig. 3A). Lo et al. attributed these differences to different levels of cognitive and motor activation during the stance and swing phases of gait; co-contractions had significant associations with physical measures during the stance phase, while co-contractions had significant associations with cognitive measures during the swing phase [26]. Older adults use muscle co-contraction to stiffen joints to compensate for poor postural control [10], and lifting, forward propulsion, and lowering the foot during the swing phase demand greater cognitive resources than the stance phase [26]. This likely explains the difference in knee muscle co-contraction between the two age groups only during the swing phase of walking. This also explains the lack of difference in ankle muscle co-contraction between the two age groups, as the muscles crossing the ankle joint do not contribute to lifting, forward propulsion, and lowering of the foot during the swing phase. The differences in cognitive and motor activation levels in stance and swing phases may be less pronounced during stair ascent and descent activities. We found greater knee muscle co-contraction in old compared to young adults from the entire cycle (Fig. 2A), and in the stance and swing phases of stair ascent (Fig. 3B). This trend is likely also true for

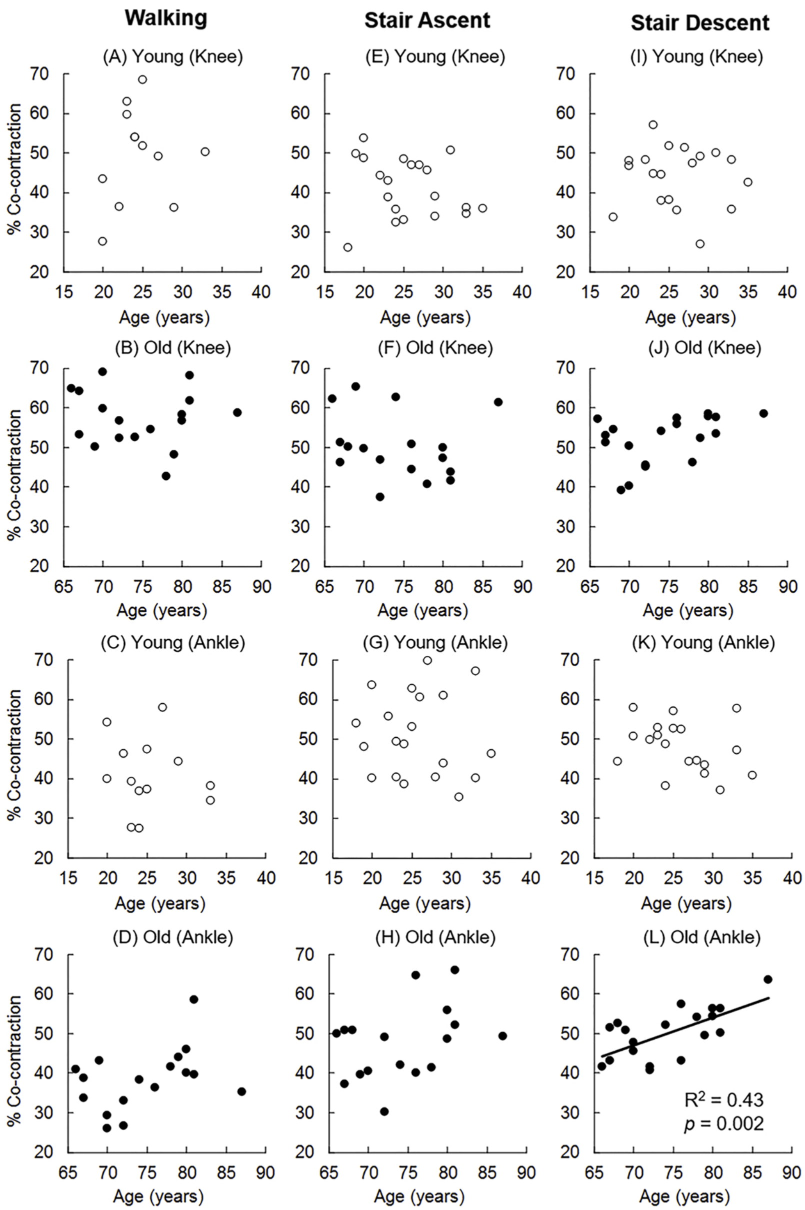

Fig. 4. Relationship between age and muscle co-contraction during the entire cycle of a walking (A–D), stair ascent (E–H), and stair descent (I–L) activities evaluated at the knee and ankle joints of young and old adults. At the knee joint, muscle co-contraction was evaluated between the vastus lateralis and biceps femoris muscles. At the ankle joint, muscle co-contraction was evaluated between the tibialis anterior and medial gastrocnemius muscles. The regression line represents a significant relationship (R^2 = 0.43, p = 0.002) in old adults at the ankle joint during stair descent. The relationship between age and muscle co-contraction was close to significance (R^2 = 0.20, p = 0.057) in old adults at the knee joint during stair descent (J).

stair descent, with the difference in the means of knee muscle co-contractions being close to significance (p = 0.025) during the stance phase (Figs. 2A and 3 C).

Our results are consistent with the previous two studies investigating muscle co-contraction in healthy young and old adults during stair ascent and descent activities [7,19]. Hortobagyi et al. found greater muscle co-contraction in old compared to young adults at the knee joint during stair ascent and descent, with the ankle joint not evaluated [7]. Larsen et al. reported 16.8% and 19.2% greater knee muscle co-contractions during the stance phase of stair ascent and descent, respectively [19]; in comparison, we found 21% and 13% (close to significance, p = 0.025) greater knee muscle co-contractions during the stance phase of stair ascent and descent, respectively (Fig. 3B, C). Larsen et al. did not evaluate muscle co-contractions during the swing phase of stair ascent and descent [19]; to the best of our knowledge, this present study is the first to report muscle co-contraction during the swing phase of stair ascent and descent activities. These results epitomize the greater demands required during stair use than level walking.

We found no gender-based difference in muscle co-contraction at the knee and ankle joints during walking, stair ascent, and stair descent activities (Fig. 5). Our results contradict Mengarelli et al., who reported consistently greater ankle muscle co-contractions in females compared to males during walking [20]. They attributed these gender differences to "a female tendency for a more complex muscular strategy during gait" [20]. We agree with Mengarelli et al. that there are gender-based differences in hip, pelvis, and knee kinematics [30,31], and myoelectric activity [32]; however, evidence of a more complex muscular strategy in females compared to males is sparse. Further investigation is required to understand the prevalence and potential causes of gender-based differences in muscle co-contraction. Next, Mengarelli et al. did not evaluate muscle co-contractions at the knee joint, or during stair ascent and stair descent [20]; these are novel contributions of our present study.

A limitation of this study is that we only acquired EMG activations from the medial gastrocnemius muscle of the triceps surae. The medial gastrocnemius contributes ˜24% to the triceps surae, with the remaining contributions from the soleus (˜60%) and lateral gastrocnemius (˜16%) muscles [33]. An average muscle activation of all three muscles or relative to their contributions to triceps surae would be a more complete approach. A second limitation is that we did not acquire maximum isometric activation data from the subjects in this study.

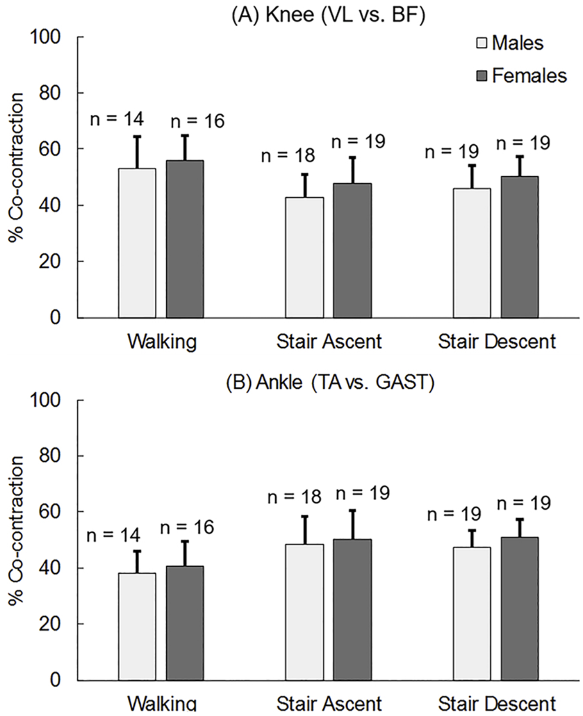

Fig. 5. Average (+1 SD) muscle co-contractions for males and females during walking, stair ascent, and stair descent activities evaluated at the (A) knee and (B) ankle joints. Average muscle co-contractions from the entire cycle (stance and swing) of the three activities are shown. At the knee joint, muscle co-contractions were evaluated between the vastus lateralis (VL) and biceps femoris (BF) muscles. At the ankle joint, muscle co-contractions were evaluated between the tibialis anterior (TA) and medial gastrocnemius (GAST) muscles. The number of participants in each group are shown next to the bars.

Using the dynamic normalization technique, direct comparison of EMG values between the two age groups may be influenced by the differences in maximal activations during the different phases of an activity due to differing kinematic strategies in the two age groups. Maximal isometric activation data would provide us a better way to normalize our EMG data than the dynamic normalization technique. A third limitation of this study is that our results are based on a single method of calculating muscle co-contraction from EMG data, that is, by evaluating the ratio of the common area to total area under the EMG signal curves of a muscle pair [1,26,29]. Although this method is well established and commonly used, there are other valid methods for calculating muscle co-contraction from EMG data [34–37]. It is unclear if the conclusions of this study can be applied to other EMG-based methods to calculate muscle co-contraction. A direct comparison of muscle co-contraction results using different EMG-based methods would test the generality of our findings, and may provide clarity by tying together the disparate studies in the literature and building a cohesive understanding on muscle co-contraction during activities of daily living. A fourth potential limitation of this study is that we used an EMG-based method to determine muscle co-contraction during walking, stair ascent, and stair descent. Although greater EMG magnitude is related to greater muscle force [38,39], this relationship is not linear [40], especially during dynamic activities like walking and stair ascent/descent [12,41]. Electromyography-based methods are not able to distinguish between the force production capacity of the agonist and antagonist muscles. For example, an EMG-based method to calculate muscle co-contraction at the ankle joint does not account for the plantar flexor muscles being several times stronger than the dorsiflexor muscles [42]. As a result, the ability of EMG-based methods to quantify actual muscle co-contraction during dynamic activities remains unclear [12,41]. On the other hand, EMG-to-force models to calculate muscle co-contractions using joint moments [12,41] are time consuming and difficult to translate to clinics. As such, EMG-based methods remain the standard for quantifying muscle co-contraction in clinical settings.

Muscle co-contraction is an accepted clinical measure to understand the effects of aging and pathology on muscle control strategies [12,13]. Our present study provides new evidence in support of greater muscle co-contraction in old compared to young adults at the knee joint during walking, stair ascent, and stair descent activities. Based on our findings, we recommend clinical evaluation to quantify the effects of aging through muscle co-contraction to include the knee joint during dynamic activities like walking and stair use, and independent evaluation of the stance and swing phases of an activity. Future work includes analysis of muscle co-contractions in relation to joint kinematic differences, and during more detailed gait events, including single and double support and concentric and eccentric muscle activity.

Declaration of Competing Interest

The authors have no conflict of interest to disclose related to this manuscript.

Acknowledgments

We thank Xu Xu, Chien-Chi Chang, Shiu-Ling Chiu for initial planning of the study. We thank Niall O'Brian, Jacob Banks, and Amanda Rivard for data collection and initial data processing. This work was supported in part by the Fonds de Recherche du Québec–Santé post-doctoral training program (Dixon #33358).

References

[1] D.A. Winter, Biomechanics and Motor Control of Human Movement, 4th ed., John Wiley & Sons, New York, NY, 2005.

[2] M. Darainy, D.J. Ostry, Muscle cocontraction following dynamics learning, Exp. Brain Res. 190 (2) (2008) 153–163, https://doi.org/10.1007/s00221-008-1457-y.

[3] J.J. O'Connor, Can muscle co-contraction protect knee ligaments after injury or repair? J. Bone Joint Surg. Br. 75 (1) (1993) 41–48, https://doi.org/10.1302/0301-620X.75B1.8421032.

[4] S. Hirokawa, M. Solomonow, Z. Luo, Y. Lu, R. D'Ambrosia, Muscular co-contraction and control of knee stability, J. Electromyogr. Kinesiol. 1 (3) (1991) 199–208, https://doi.org/10.1016/1050-6411(91)90035-4.

[5] P.C. Dixon, S. Gomes, R.A. Preuss, S.M. Robbins, Muscular co-contraction is related to varus thrust in patients with knee osteoarthritis, Clin. Biomech. (Bristol, Avon) 60 (2018) 164–169, https://doi.org/10.1016/j.clinbiomech.2018.10.021.

[6] J.A. Zeni, K. Rudolph, J.S. Higginson, Alterations in quadriceps and hamstrings coordination in persons with medial compartment knee osteoarthritis, J. Electromyogr. Kinesiol. 20 (1) (2010) 148–154, https://doi.org/10.1016/j.jelekin.2008.12.003.

[7] T. Hortobagyi, C. Mizelle, S. Beam, P. DeVita, Old adults perform activities of daily living near their maximal capabilities, J. Gerontol. A Biol. Sci. Med. Sci. 58 (5) (2003) 453–460, https://doi.org/10.1093/gerona/58.5.M453.

[8] M.H. Woollacott, Age-related changes in posture and movement, J. Gerontol. 48 (1993) 56–60, https://doi.org/10.1093/geronj/48.Special_Issue.56.

[9] J.M. Hausdorff, Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking, Hum. Mov. Sci. 26 (4) (2007) 555–589, https://doi.org/10.1016/j.humov.2007.05.003.

[10] N. Benjuya, I. Melzer, J. Kaplanski, Aging-induced shifts from a reliance on sensory input to muscle cocontraction during balanced standing, J. Gerontol. A Biol. Sci. Med. Sci. 59 (2) (2004) 166–171, https://doi.org/10.1093/gerona/59.2.M166.

[11] D.S. Peterson, P.E. Martin, Effects of age and walking speed on coactivation and cost of walking in healthy adults, Gait Posture 31 (3) (2010) 355–359, https://doi.org/10.1016/j.gaitpost.2009.12.005.

[12] H. Souissi, R. Zory, J. Bredin, P. Gerus, Comparison of methodologies to assess muscle co-contraction during gait, J. Biomech. 57 (2017) 141–145, https://doi.org/10.1016/j.jbiomech.2017.03.029.

[13] A.R. Den Otter, A.C. Geurts, T. Mulder, J. Duysens, Gait recovery is not associated with changes in the temporal patterning of muscle activity during treadmill walking in patients with post-stroke hemiparesis, Clin. Neurophysiol. 117 (1) (2006) 4–15, https://doi.org/10.1016/j.clinph.2005.08.014.

[14] T. Hortobagyi, S. Solnik, A. Gruber, P. Rider, K. Steinweg, J. Helseth, et al., Interaction between age and gait velocity in the amplitude and timing of antagonist muscle coactivation, Gait Posture 29 (4) (2009) 558–564, https://doi.org/10.1016/j.gaitpost.2008.12.007.

[15] C.Z. Hallal, N.R. Marques, D.H. Spinoso, E.R. Vieira, M. Goncalves, Electromyographic patterns of lower limb muscles during apprehensive gait in younger and older female adults, J. Electromyogr. Kinesiol. 23 (5) (2013)

1145–1149, https://doi.org/10.1016/j.jelekin.2013.06.006.

[16] J.R. Franz, R. Kram, How does age affect leg muscle activity/coactivity during uphill and downhill walking? Gait Posture 37 (3) (2013) 378–384, https://doi.org/10.1016/j.gaitpost.2012.08.004.

[17] O.S. Mian, J.M. Thom, L.P. Ardigo, M.V. Narici, A.E. Minetti, Metabolic cost, mechanical work, and efficiency during walking in young and older men, Acta Physiol. Oxf. (Oxf) 186 (2) (2006) 127–139, https://doi.org/10.1111/j.1748-1716.2006.01522.x.

[18] K. Nagai, M. Yamada, K. Uemura, Y. Yamada, N. Ichihashi, T. Tsuboyama, Differences in muscle coactivation during postural control between healthy older and young adults, Arch. Gerontol. Geriatr. 53 (3) (2011) 338–343, https://doi.org/10.1016/j.archger.2011.01.003.

[19] A.H. Larsen, L. Puggaard, U. Hamalainen, P. Aagaard, Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing, J. Electromyogr. Kinesiol. 18 (4) (2008) 568–580, https://doi.org/10.1016/j.jelekin.2006.12.008.

[20] A. Mengarelli, E. Maranesi, V. Barone, L. Burattini, S. Fioretti, F. Di Nardo, Evaluation of gender-related differences in co-contraction activity of shank muscles during gait, Conf. Proc. IEEE Eng. Med. Biol. Soc. 2015 (2015) 6066–6069, https://doi.org/10.1109/EMBC.2015.7319775.

[21] S.L. Chiu, C.C. Chang, J.T. Dennerlein, X. Xu, Age-related differences in inter-joint coordination during stair walking transitions, Gait Posture 42 (2) (2015) 152–157, https://doi.org/10.1016/j.gaitpost.2015.05.003.

[22] M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, J. Gainey, G. Gorton, G.V. Cochran, Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait, J. Orthop. Res. 7 (6) (1989) 849–860, https://doi.org/10.1002/jor.1100070611.

[23] Y. Jian, D.A. Winter, M.G. Ishac, L. Gilchrist, Trajectory of the body COG and COP during initiation and termination of gait, Gait Posture 1 (1993) 9–22, https://doi.org/10.1016/0966-6362(93)90038-3.

[24] D.J. Rutherford, C.L. Hubley-Kozey, W.D. Stanish, Maximal voluntary isometric contraction exercises: a methodological investigation in moderate knee osteoarthritis, J. Electromyogr. Kinesiol. 21 (1) (2011) 154–160, https://doi.org/10.1016/j.jelekin.2010.09.004.

[25] A. Perotto, E.F. Delagi, J. Iazzetti, D. Morrison, Anatomical Guide for the Electromyographer, 4th ed., Charles C. Thomas, Springfield, IL, 2005.

[26] J. Lo, O.Y. Lo, E.A. Olson, D. Habtemariam, I. Iloputaife, M.M. Gagnon, et al., Functional implications of muscle co-contraction during gait in advanced age, Gait Posture 53 (2017) 110–114, https://doi.org/10.1016/j.gaitpost.2017.01.010.

[27] P.C. Dixon, K. Jansen, I. Jonkers, J. Stebbins, T. Theologis, A.B. Zavatsky, Muscle contributions to centre of mass acceleration during turning gait in typically developing children: a simulation study, J. Biomech. 48 (16) (2015) 4238–4245, https://doi.org/10.1016/j.jbiomech.2015.10.028.

[28] A.J. Meyer, C. Patten, B.J. Fregly, Lower extremity EMG-driven modeling of walking with automated adjustment of musculoskeletal geometry, PLoS One 12 (7) (2017) e0179698 https://www.ncbi.nlm.nih.gov/pubmed/28700708.

[29] S. Hesse, B. Brandl-Hesse, U. Seidel, B. Doll, M. Gregoric, Lower limb muscle activity in ambulatory children with cerebral palsy before and after the treatment with Botulinum toxin A, Restor. Neurol. Neurosci. 17 (1) (2000) 1–8 https://www.ncbi.nlm.nih.gov/pubmed/11490071.

[30] R.A. Malinzak, S.M. Colby, D.T. Kirkendall, B. Yu, W.E. Garrett, A comparison of knee joint motion patterns between men and women in selected athletic tasks, Clin. Biomech. Bristol Avon (Bristol, Avon) 16 (5) (2001) 438–445, https://doi.org/10.1016/S0268-0033(01)00019-5.

[31] E.S. Chumanov, C. Wall-Scheffler, B.C. Heiderscheit, Gender differences in walking and running on level and inclined surfaces, Clin. Biomech. (Bristol, Avon) 23 (10) (2008) 1260–1268, https://doi.org/10.1016/j.clinbiomech.2008.07.011.

[32] F. Di Nardo, A. Mengarelli, E. Maranesi, L. Burattini, S. Fioretti, Gender differences in the myoelectric activity of lower limb muscles in young healthy subjects during walking, Biomed. Signal Process. Control 19 (2015) 14–22, https://doi.org/10.1016/j.bspc.2015.03.006.

[33] C.I. Morse, J.M. Thom, O.S. Mian, A. Muirhead, K.M. Birch, M.V. Narici, Muscle strength, volume and activation following 12-month resistance training in 70-year-old males, Eur. J. Appl. Physiol. 95 (2–3) (2005) 197–204 https://www.ncbi.nlm.nih.gov/pubmed/16003538.

[34] K.S. Rudolph, M.J. Axe, L. Snyder-Mackler, Dynamic stability after ACL injury: who can hop? Knee Surg. Sports Traumatol. Arthrosc. 8 (5) (2000) 262–269, https://doi.org/10.1007/s001670000130.

[35] V.B. Unnithan, J.J. Dowling, G. Frost, B. Volpe Ayub, O. Bar-Or, Cocontraction and phasic activity during GAIT in children with cerebral palsy, Electromyogr. Clin. Neurophysiol. 36 (8) (1996) 487–494 https://www.ncbi.nlm.nih.gov/pubmed/8985677.

[36] G. Frost, J. Dowling, K. Dyson, O. Bar-Or, Cocontraction in three age groups of children during treadmill locomotion, J. Electromyogr. Kinesiol. 7 (3) (1997) 179–186, https://doi.org/10.1016/S1050-6411(97)84626-3.

[37] K. Falconer, D.A. Winter, Quantitative assessment of co-contraction at the ankle joint in walking, Electromyogr. Clin. Neurophysiol. 25 (2–3) (1985) 135–149 https://www.ncbi.nlm.nih.gov/pubmed/3987606.

[38] C. Richards, J.S. Higginson, Knee contact force in subjects with symmetrical OA grades: differences between OA severities, J. Biomech. 43 (13) (2010) 2595–2600, https://doi.org/10.1016/j.jbiomech.2010.05.006.

[39] T.M. Griffin, F. Guilak, The role of mechanical loading in the onset and progression of osteoarthritis, Exerc. Sport Sci. Rev. 33 (4) (2005) 195–200, https://doi.org/10.1097/00003677-200510000-00008.

[40] T.S. Buchanan, D.G. Lloyd, K. Manal, T.F. Besier, Neuromusculoskeletal modeling: estimation of muscle forces and joint moments and movements from measurements of neural command, J. Appl. Biomech. 20 (4) (2004) 367–395, https://doi.org/10.1123/jab.20.4.367.

[41] B.A. Knarr, J.A. Zeni Jr., J.S. Higginson, Comparison of electromyography and joint moment as indicators of co-contraction, J. Electromyogr. Kinesiol. 22 (4) (2012) 607–611, https://doi.org/10.1016/j.jelekin.2012.02.001.

[42] T. Fukunaga, R.R. Roy, F.G. Shellock, J.A. Hodgson, V.R. Edgerton, Specific tension of human plantar flexors and dorsiflexors, J. Appl. Physiol. 80 (1) (1985) 158–165, https://doi.org/10.1152/jappl.1996.80.1.158 (1996).