European Journal of Applied Physiology (2019) 119:61–71
https://doi.org/10.1007/s00421-018-3999-4

ORIGINAL ARTICLE

The influence of knee extensor fatigue on lower extremity muscle activity during chair rise in young and older adults

Megan A. Bryanton[1,3] · **Martin Bilodeau**[2,3]

Received: 27 November 2017 / Accepted: 20 September 2018 / Published online: 13 October 2018

Abstract

Purpose The purpose of this investigation was to evaluate alterations in muscular effort and temporal characteristics of their activity during the sit-to-stand (STS) due to isolated fatiguing of the knee extensors, as indicated by declines in torque output.

Methods Surface electromyography of the lower extremity was recorded in healthy young ($n = 11$) and older ($n = 11$) adults as they ascended from a seated position, before and after dynamic knee extension exercise.

Results Knee extensor fatigue caused significant increases in soleus, gastrocnemius, and gluteus maximus relative effort (%MVC) in both age groups during the STS task. Rectus femoris %MVCs in both young and older adults significantly increased to similar extents throughout the STS movement, whereas vastus lateralis amplitudes only increased in preparation for seat-off. Muscle temporal characteristics appeared to generally be invariant with fatigue, except for earlier activation onset for the ankle musculature in older adult participants.

Conclusions These findings demonstrate that isolated knee extension fatiguing exercise caused compensatory changes in muscle activation patterns and increased reliance of non-fatigued muscles at the ankle and hip as well as increased activity of synergist muscles during the STS. Moreover, this occurred to similar extents in older adults who had lower knee extensor strengths and greater quadriceps %MVCs in comparison to their younger counterparts, regardless of fatigue condition.

Keywords Aging · Fatigue · Sit-to-stand · Electromyography · Knee extensors

Abbreviations

BF	Biceps femoris
EMG	Electromyography
GAS	Gastrocnemius
GMax	Gluteus maximus
MVC	Maximal voluntary contraction
RF	Rectus femoris
SOL	Soleus
STS	Sit-to-stand
VL	Vastus lateralis

Communicated by Lori Ann Vallis.

✉ Megan A. Bryanton
mbrya038@uottawa.ca

1 School of Human Kinetics, University of Ottawa, Ottawa, ON, Canada

2 School of Rehabilitation Sciences, University of Ottawa, Ottawa, ON, Canada

3 Aging and Movement Laboratory, Bruyère Research Institute (BRI), 43 Bruyère St., Ottawa, ON K1N 5C8, Canada

Introduction

Age-related declines in maximal strength and force control capabilities of the knee extensors have deleterious effects on functional capabilities in older populations, particularly when performing transfer tasks of daily living that involve large muscular demands such as standing up from a seated position (i.e. sit-to-stand; STS) (Bassey et al. 1992; Bohannon 2009; Brech et al. 2013; Carville et al. 2007; Corrigan and Bohannon 2001; Eriksrud and Bohannon 2003; Hortobágyi et al. 2003; Hughes et al. 1996; Ikezoe et al. 2011; Kallio et al. 2012; LeRoche et al. 2010; Muhlberg and Sieber 2004; Petrella et al. 2005; Roos et al. 1997; van Roie et al. 2011). The STS is a multi-articular movement and a basic skill required for independent living that involves substantially greater muscular efforts in the knee extensor musculature, in comparison to the ankle plantar flexors and hip extensors (Bieryla et al. 2009; Burnfield et al. 2012). For example, Burnfield et al. (2012) noted that during the ascending phase of the STS, vastus lateralis (VL) surface electromyography (EMG) signal values peaked at 63% of their maximal voluntary contraction (MVC) levels in healthy adults; whereas hamstring and gluteus maximus (GMax) peaked at 14% and 21%, respectively. Biomechanical investigations have indicated knee extensor strength as a primary limiting factor of STS performance with aging, as near maximal efforts (80–100%MVC) have been observed in older adults (Hortobágyi et al. 2003; Hughes et al. 1996; Savelberg et al. 2007); however, contributions of other lower extremity muscle groups were not evaluated in older populations.

Previous investigations have suggested that older persons have a greater ability to resist fatigue in comparison to younger adult participants, as indicated by greater endurance times when subjected to sustained submaximal isometric contractions of similar relative loads (Bilodeau et al. 2001; Hunter et al. 2004; Kent-Braun and Ng 1999). However, age differences in endurance times appear to be negligible during dynamic contractions at high efforts (Avin and Law 2011), such as those required from the knee extensor musculature during the STS task (Burnfield et al. 2012; Hortobágyi et al. 2003; Wretenberg and Arborelius 1994). Considering this, although older persons may have sufficient strength reserves to meet extensor force requirements to rise from a seated position, they may develop fatigue more readily and disproportionately across the lower extremities in comparison to their younger counterparts. In turn, a lesser extent of the resultant force declines with repetitive actions would be sufficient to impair STS performance in older adults and may allude to the role of reduced knee extensor strength reserves in impacting autonomy and quality of life with aging.

Strength limitations and reduced force-generating capabilities have been suggested to result in compensatory STS strategies through shifting of muscular demands to more evenly distribute efforts (Hortobágyi et al. 2003; Puniello et al. 2001; Savelberg et al. 2007; van der Heijden et al. 2009; Yoshioka et al. 2007); however, EMG evidence to support this is lacking. Regardless, compensatory muscle strategies may occur within a muscle group synergy, such as through earlier pre-activation and altered co-activation, within specific muscle pairs, as well as across joints (Akima et al. 2002, 2004; Bonnard et al. 1994). For example, Bonnard et al. (1994) found that with repetitive hopping, fatigue accumulated in the ankle plantar flexor musculature resulted in increased activity of the rectus femoris (RF), as well as earlier pre-activation of the gastrocnemius (GAS) to sustain performance. Moreover, temporal shifting in muscular contributions to the activity may also occur to improve movement efficiency by limiting simultaneous peak activities of agonist–antagonist muscle pairs (Chiu et al. 2012; Gregoire et al. 1984). Considering all this, there may be several degrees of freedom that one may take advantage of in the face of reduced knee extensor performance; however age-dependent compensatory actions due to fatigue have not been thoroughly investigated for a demanding multi-joint, such as the STS.

Muscular coordination involved in successful movement execution can be evaluated by comparing the distribution of activation intensities and temporal patterns with or between muscle synergies (Hug 2011). Using such measurement techniques, this investigation aimed to evaluate compensatory STS strategies in young and older adult participants, due to reduced force-generating capabilities of the knee extensors with isolated fatiguing exercise. It was hypothesized that knee extensor torque declines, due to high- and moderate-intensity dynamic fatiguing contractions, would cause compensatory shifting of muscular demands amongst the lower extremities, as indicated by increased EMG amplitudes of the ankle plantar flexor and hip extensor musculature. Specifically, if the extent of magnitude increases is dependent on a lack of available knee extensor strength reserves, they would be most apparent when available torque-generating capabilities of the knee extensors are reduced and occur to a greater extent in older adults due to lower knee extensor strength reserves.

Methods

Participants

Twenty-two healthy adult men and women between the ages of 18–35 years (i.e., young adult, $n = 11$; 5 females) and 60–85 years (i.e., older adult, $n = 11$; 5 females) recruited from the community as a convenience sample participated in this investigation. Exclusion criteria for participants included having previous lower extremity or lower back orthopedic and musculoskeletal injuries that prevented the exercise from being performed safely, as well as taking any medications that may have affected balance. Participants were instructed to refrain from any strenuous lower extremity activities prior to visiting the laboratory. Ethics approval was obtained from the University of Ottawa and Bruyère Research Institute research ethics board, and informed consent was obtained prior to testing. In addition to individual anthropometrics of height and body weight, the Godin-Leisure Time Questionnaire was asked to be filled out by participants and scores were calculated as an indication of the type and frequency of physical activity levels in young and older participants. Specifically, this self-explanatory questionnaire of the participant's usual leisure-time exercise habits consider the frequency and duration of strenuous, moderate and light activities over a 7-day period, outside of possible employment (i.e., non-leisure activities). Such activities include but are not limited to: running (strenuous exercise where heart beats rapidly), fast walking (moderate exercise that is not exhausting), and easy walking (mild exercise that requires minimal effort), for more than 15 min during free time (Godin and Sheppard 1997). All testing was performed during a single 90 min laboratory visit.

Procedures

EMG recordings

Electromyography signals of the lower extremity musculature were collected on the dominant limb, which was deemed as the leg that the participants would kick a soccer ball with. EMG signals from the RF, VL, biceps femoris long head (BF), soleus (SOL), medial head of the gastrocnemius (GAS), and the GMax were recorded during STS and fatigue testing procedures with bipolar surface electrodes of 1 mm width and 10 mm length, and a 10 mm center-to-center interelectrode distance (DE-2.1, Delsys Inc., Boston, USA). All electrodes were placed in a direction parallel to the general direction of muscle fibers for a given muscle. A reference electrode was positioned approximately 6 cm distal to the inferior pole of the patella over the bony surface of the tibia. EMG signals were recorded using the Bagnoli 16 EMG system (Delsys Inc., Boston, USA) at a sampling rate of 2000 Hz and amplification between 100× and 10,000×, and bandpass between 20 and 450 Hz using Spike2 software (Cambridge Electronic Design Limited, Cambridge, ENG). EMG signals were then rectified and smoothed using root-mean square with a 50 ms window. All root-mean square signal amplitudes were then normalized to peak mean values of a 50 ms window from an isometric maximal voluntary contraction (MVC) obtained at the beginning of the laboratory visit for each respective muscle group prior to any STS testing or fatigue protocol (Fig. 1). Electrode placement, participant positioning, and normalization isometric contractions were performed according to SENIAM recommendations (Hermens et al. 1999). The order of muscle group MVC collected was not randomized in an attempt to maintain consistency in collection procedures between participants; however, multiple attempts were asked of participants if the researcher deemed necessary to ensure maximal attempts were being performed. Normalized signal values were chosen, as the absolute amplitude of the surface EMG signal provides a poor index of neural drive to the muscle and is also not appropriate for comparisons between conditions and persons.

Isokinetic dynamometry and fatigue protocol

To determine if the extent of knee extensor torque generating declines may influence the compensatory muscle strategy adopted when rising from a chair, both young and older adults were asked to perform repetitive bilateral submaximal dynamic knee extension contractions on an isokinetic dynamometer (Biodex System 3 ProH, Biodex Medical Systems, Shirley, USA) at 60° per second (i.e., approximate time it takes to perform an STS repetition) for a 90° to 0° range of motion at the knee. First, participants performed a dynamic warm-up which consisted of three sets of submaximal bilateral leg extension efforts at this speed and range of motion with approximately 60 s rest in between sets. Participants were then asked to perform a minimum of three maximal knee extensor attempts, with 60 s rest between attempts, of which peak torque outputs were displayed and measured on an oscilloscope. If the participant's values continued to increase by the third set, a fourth attempt was performed. From this, 80% and 50% of the participant's highest attempt was used for the subsequent fatigue protocols.

For the isolated fatigue of the knee extensors, two intensities (80% and 50% of their predetermined maximal dynamic knee extensor peak torque) were used for fatiguing protocols. Consecutive repetitions were performed at the desired intensity by observing their torque outputs displayed on the oscilloscope during the fatigue set, until the participant was no longer able to achieve the desired force output. Strong verbal encouragements

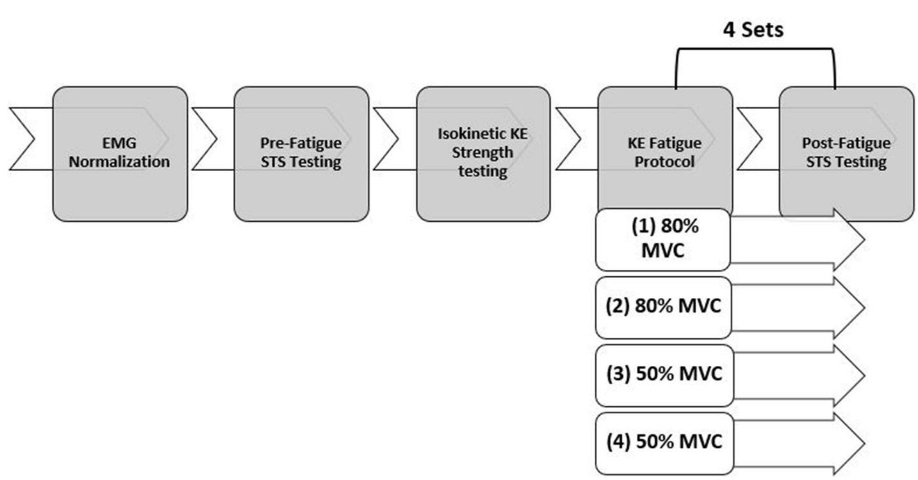

Fig. 1 Schematic diagram of testing protocol sequence. All isokinetic testing protocols were performed at 60° per second over 90° of knee extension (90–0 degrees of flexion)

were provided to ensure maximal efforts. The end of the fatigue set was determined by the researcher when the participant was no longer able to achieve the peak desired torque output intensity threshold on the display for three consecutive knee extension repetitions. Each fatigue set was then followed immediately by the STS protocol task described below. Two rounds of fatigue were performed at each intensity and later averaged to increase the validity of measurements, for a total of four sets, starting at the highest 80% intensity, followed by 50% intensity fatigue protocols [for example: (1) 80%, (2) 80%, (3) 50%, (4) 50%] as the aim was to reduce the force-generating capabilities by first 20% (i.e., 100% – 80% = 20%) and then 50% (i.e., 100% – 50% = 50%) of their relative maximal strength reserves, since this number of fatigue protocols in one setting would affect each set incrementally.

STS protocol

Participants were instructed to sit on an armless and backless bench with a force plate fixed on top (Bertec Corporation, Columbus, OH, USA) in a comfortable erect posture with arms folded across their chest to deter the use of arm movement. Initial foot placement was marked on two additional force platforms that were placed beneath their feet, to prevent shifting of feet during the STS testing protocols. Seat height was adjusted to 80% of the participant's lower limb length. Participants were instructed to stand up from the chair to a fully extended erect posture at a self-selected, comfortable speed, pause briefly, and then return to a seated position when signaled by the researcher. Reaction forces provided by the seat force platform were synched with EMG acquisitions into Spike2 at a sampling frequency of 100 Hz, which provided an indication of the commencement of forward body movement when initiating the STS, as well as the instant that contact with the buttocks was lost with the seat. STS testing was performed prior to and after dynamic fatiguing of the knee extensors. Three sets of three STS repetitions were performed for the non-fatigued conditions with 1-min rest intervals between sets. For each post-fatigue STS set, participants were asked to then perform three STS repetitions, for a total of two sets after fatiguing intensity of 80% (Post-80) of their dynamic maximal knee extensor strengths, and two sets after the 50% (Post-50) fatigue intensity. Transition time between the knee extensor fatigue protocol to commencing of first post-fatigue STS repetition was immediate to reduce possible fatigue recovery time. Participants were assisted by the researchers to the STS seat that was located in close proximity to the dynamometer to prevent any loss of balance and risk of injury.

Data analysis

The primary analyses compared changes in mean EMG muscle activation intensities (%MVC) during the preparatory (initiation of forward body displacement until loss of contact with the buttocks) and ascending (from seat-off until full upright posture achieved) to provide a comprehensive evaluation of muscle activity over the movement phase (Renshaw et al. 2010; Vigotsky et al. 2015). Secondly, instances of muscle onset and peak activity timings relative to seat-off were also calculated using Spike as indicated by 5 standard deviations above resting signals to detect changes in temporal characteristic with aging and fatigue.

For each fatigue condition, values were averaged between sets for each participant. With this, a mixed-model ANOVA with one between-subjects (age: young vs. older adults) and one repeated-measure (fatigue intensity; pre-fatigue vs. Post-80% vs. Post-50%) was used for significance testing for each muscle's %MVC, onset time and time of peak activity. Where appropriate, Tukey HSD was used for post hoc comparisons. Cohen's f effect size statistic was used to report an index of the size of differences, where a value of 0.1, 0.25, and 0.4 indicates small, moderate, and large effect sizes, respectively. Independent *t* tests were performed to compare dynamic knee extensor strengths as well as Godin physical activity scores between younger and older adults. The alpha level was set a priori at $\alpha = 0.05$.

Results

Statistical analysis revealed a significant group difference in dynamic knee extensor strengths; older participants had lower maximal knee extensor torque values compared to young adults, when body weight was accounted for (t (20): 3.70, $p > 0.001$). There were no significant group differences in for Godin–Leisure Time Scores (t (20): 0.343, $p = 0.185$); both young and older groups were matched for physical activity level. All other subject demographics and anthropometrics are summarized in Table 1.

Preparatory phase %MVCs

Mauchly's test of sphericity were found to be significant during the preparatory phase for the RF, BF, GAS, and during the ascending phase for the VL, SOL, and GAS, and GMax ($p < 0.05$) and Greenhouse–Geisser corrections were subsequently used. For the preparatory phase of the STS, significant fatigue main effects were observed for %MVCs of the VL ($p = 0.008, f = 0.577$), RF ($p = 0.001, f = 0.636$), BF ($p = 0.012, f = 0.689$) and the GMax ($p = 0.011, f = 0.505$). In turn, significant age main effects were observed for the VL ($p < 0.001, f = 1.158$) and RF ($p < 0.001, f = 1.321$);

Table 1 Subject characteristics (± *SDs*)

Group	Age (years)	Body mass (kg)	Height (cm)	GLTQ	KE MVC (60°/s) (Nm/kg)
Young ($n=11$; 5 females)	27.4 (*4.5*)	74.4 (*16.7*)	168.6 (*10.8*)	39.2 (*12.5*)	**4.4 (*0.7*)**
Old ($n=11$; 5 females)	68.4 (*4.1*)	70.7 (*15.1*)	172.0 (*11.0*)	54.0 (*34.1*)	**3.1 (*0.8*)***

*Significant age group difference from young

older adults had higher %MVC in comparison to younger adults. No significant fatigue × age interactions were found ($p>0.05$); however, trends toward significance were found for the VL ($p=0.077$, $f=0.388$), RF ($p=0.056$, $f=0.395$) and BF ($p=0.058$, $f=0.368$). For the ankle musculature, SOL and GAS %MVCs remained unchanged during the preparatory phase for both fatigue conditions (Fig. 2). For the knee extensor musculature, both fatigue protocols caused a significant increase in preparatory VL and RF activity in both age groups from pre-fatigue values (Post-80; $p=0.011$ and $p=0.001$, respectively, Post-50; $p=0.011$ and $p=0.046$, respectively). RF %MVC in older adults significantly increased to a greater extent for Post-50 values in comparison to Post-80 STS trials ($p=0.028$) (Fig. 3). Lastly, in both age groups, BF activity significantly increased in both groups from pre-fatigue to Post-80 and -50 only ($p=0.013$ and $p=0.045$, respectively), and decreased from Post-80 to Post-50 ($p=0.030$), while the GMax only increased from pre-fatigue to Post-80 ($p=0.003$) (Fig. 4).

Ascending phase %MVCs

For the ascending phase of the STS, significant fatigue main effects were found for the SOL ($p=0.003$, $f=0.699$), GAS ($p=0.001$, $f=0.718$), RF ($p=0.001$, $f=0.705$), and GMax ($p<0.001$, $f=1.12$). Significant age main effects were again found for the VL ($p<0.001$, $f=1.026$), RF ($p=0.003$, $f=0.760$), as well as the BF ($p=0.002$, $f=0.775$); again, older adults had higher %MVCs compared to young adults. No significant fatigue × age interaction was again found, except for a trend for the SOL ($p=0.053$, $f=0.445$). For the ankle musculature, post hoc analyses showed that SOL and GAS had higher Post-80 ($p=0.003$ and $p=0.002$) and Post-50 activities ($p=0.005$ and $p=0.002$) compared to pre-fatigue after seat-off (Fig. 2). For the quadriceps, RF activity increased in both groups from pre-fatigue values to Post-80 ($p=0.001$) and Post-50 ($p=0.003$) (Fig. 3). Lastly, GMax intensity significantly increased in both groups to the same extent from pre-fatigue to Post-80 ($p<0.001$) (Fig. 4).

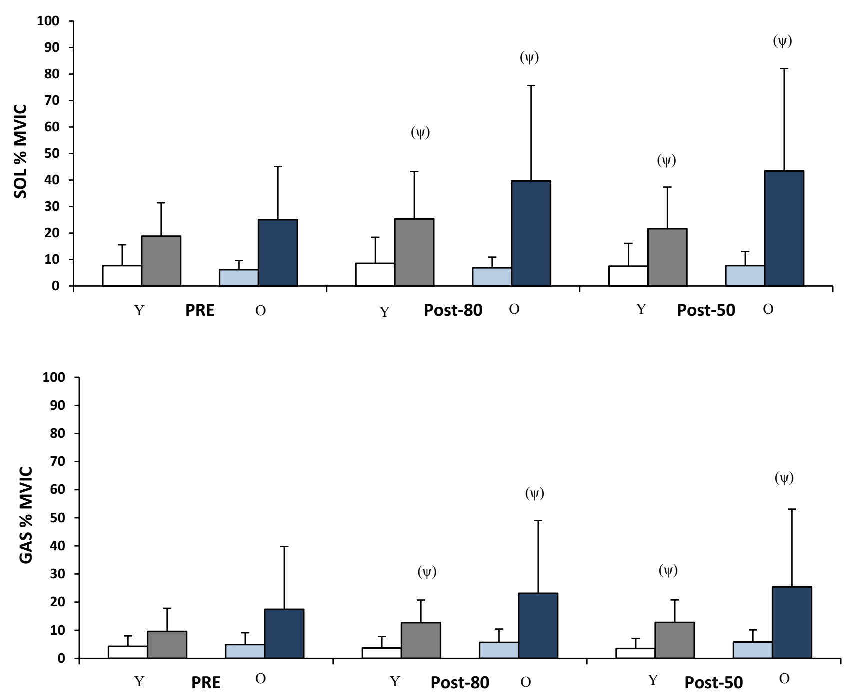

Fig. 2 Average preparatory (light) and ascending (dark) sit-to-stand %MVC of the soleus (SOL) and medial gastrocnemius (GAS) in young (Y) and older (O) adults. Error bars denote SDs. ΨSignificant difference from pre-fatigue baseline conditions. ΨΨSignificant difference from previous condition. *Significant difference from young adults

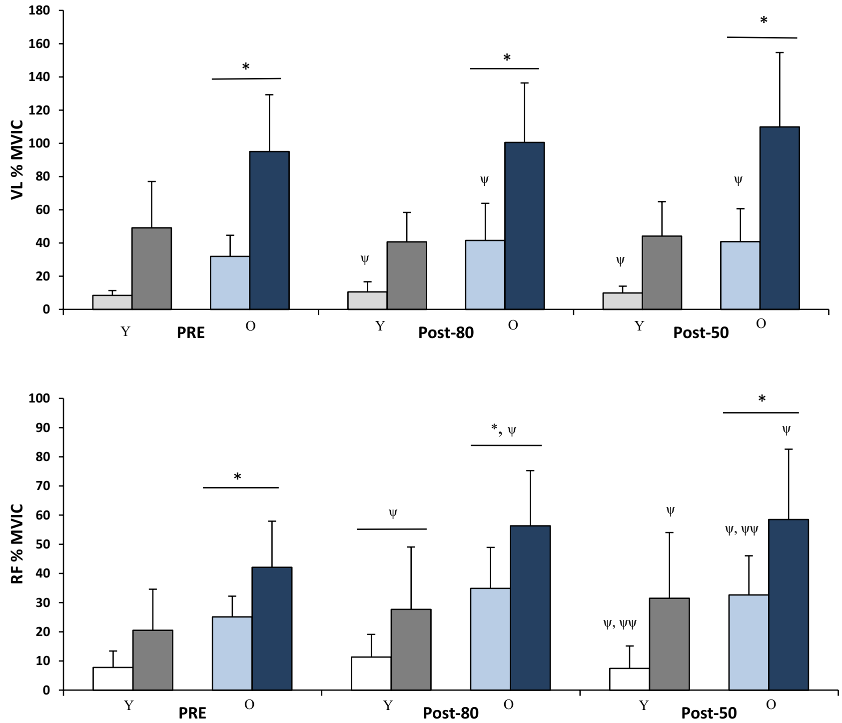

Fig. 3 Average preparatory (light) and ascending (dark) sit-to-stand %MVC of the vastus lateralis (VL) and rectus femoris (RF) %MVC in young (Y) and older (O) adults. Error bars denote SDs. $^{\Psi}$Significant difference from pre-fatigue baseline conditions. $^{\Psi\Psi}$Significant difference from previous condition. *Significant difference from young adults

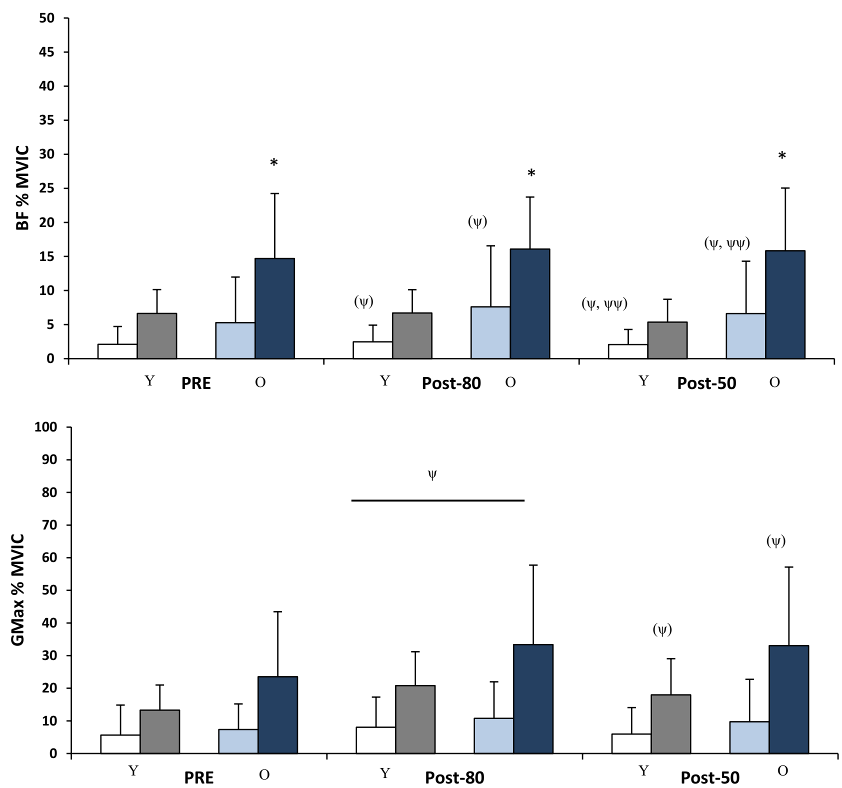

Fig. 4 Average preparatory (light) and ascending (dark) sit-to-stand %MVC of the biceps femoris long head (BF) and gluteus maximus (GMax) in young (Y) and older (O) adults. Error bars denote SDs. $^{\Psi}$Significant difference from pre-fatigue baseline conditions. *Significant difference from young adults

Temporal characteristics of muscle activity

Statistical analyses for temporal measures of muscle activity also showed significance for Mauchly's test of sphericity for the onsets of the VL, and peak timings of the BF, and Greenhouse–Geisser corrections were used. For fatigue main effects for onset times, only a trend toward significance for the RF was noted ($p = 0.068$, $f = 0.380$) (Figs. 5, 6). A

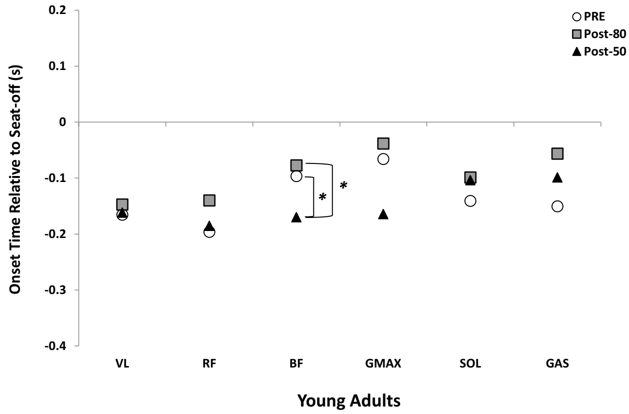

Fig. 5 Average onset times relative to seat-off (seconds; s) of young adults with respect to fatigue condition for the vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), gluteus maximus (GMax), soleus (SOL) and gastrocnemius (GAS). *Significant difference between conditions

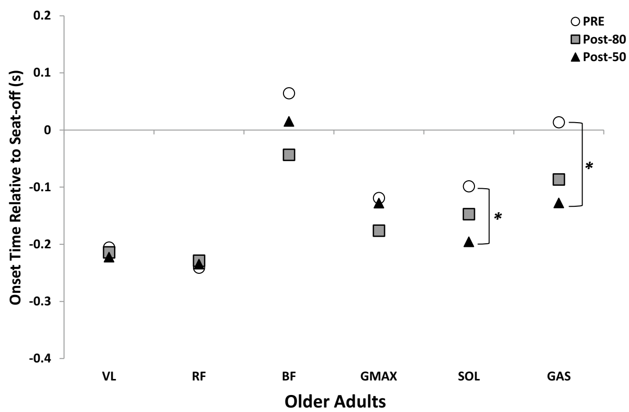

Fig. 6 Average onset times relative to seat-off (seconds; s) of older adults with respect to fatigue condition for the vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), gluteus maximus (GMax), soleus (SOL) and gastrocnemius (GAS). *Significant difference between conditions

significant fatigue × age interactions for the SOL ($p=0.008$, $f=0.520$), GAS ($p=0.006$, $f=0.537$) and GMax ($p=0.036$, $f=0.425$), with no age main effects was also found, and only a trend toward significance for the RF ($p=0.086$, $f=0.403$). Knee extensor fatigue caused earlier SOL and GAS activity onsets in older adults only (Fig. 6), while earlier GMax onset was only observed in young adults for Post-50 (Fig. 5).

No significant fatigue main effects were found for relative peak timings ($p>0.05$); however, age main effects were found for the RF ($p=0.026$, $f=0.536$), SOL ($p=0.010$, $f=0.636$) and GAS ($p=0.031$, $f=0.519$) (Table 2). RF peak activity occurred earlier closer to seat-off in older adults compared to the younger age group, while peak SOL and GAS activity occurred later at the end of the STS ascending phase in older adults.

Discussion

The primary objective of this investigation was to evaluate possible compensatory activity at the ankle and hip due to reduced force-generating capabilities of the knee extensors (i.e., quadriceps) when rising from a chair and how this may be impacted with aging. We hypothesized that the absolute strength reserves of the knee extensors were a primary determinant of the extent of compensatory muscle activity. In turn, due to their lower torque-generating capabilities, it was hypothesized that older adults would exhibit greater increases in compensatory ankle and hip musculature activity to maintain STS performance. In agreement with previous investigations (Fujita et al. 2011; Gross et al. 1998; Hughes et al. 1996), our results showed that older adults required significantly higher VL and RF %MVCs to ascend from a seated position, regardless of fatigue condition. These greater effort requirements of our older adult participants may be therefore reflective of their lower knee extensor strength reserves (Fig. 3; Table 1), despite similar Godin Leisure-Time Exercise Scores (an indication of weekly frequencies and durations of strenuous, moderate and light physical activity during leisure times). However, the fatigue conditions implemented in this current study caused similar changes in the magnitude of VL and RF activation in both age groups regardless of starting knee extensor reserves, which does not support our initial hypotheses. Findings did

Table 2 Group mean (± *SDs*) peak muscle activity timing relative to seat-off (seconds) in young (y) and older (o) adults

Muscle	Pre		Post-80%		Post-50%	
	Y	O	Y	O	Y	O
SOL	0.24 (*0.23*)	0.47 (*0.18*)*	0.29 (*0.20*)	0.49 (*0.14*)*	0.26 (*0.25*)	0.44 (*0.14*)*
GAS	0.25 (*0.22*)	0.51 (*0.30*)*	0.32 (*0.23*)	0.48 (*0.23*)*	0.25 (*0.22*)	0.49 (*0.27*)*
VL	0.08 (*0.04*)	0.11 (*0.19*)	0.06 (*0.04*)	0.08 (*0.17*)	0.05 (*0.03*)	0.06 (*0.08*)
RF	0.07 (*0.05*)	0.02 (*0.04*)*	0.08 (*0.06*)	0.03 (*0.06*)*	0.09 (*0.05*)	0.04 (*0.08*)*
BF	0.23 (*0.11*)	0.32 (*0.24*)	0.31 (*0.23*)	0.30 (*0.25*)	0.28 (*0.20*)	0.29 (*0.27*)
GMax	0.30 (*0.22*)	0.33 (*0.14*)	0.33 (*0.23*)	0.28 (*0.12*)	0.35 (*0.23*)	0.34 (*0.25*)

*Significant age group difference from young however support that isolated fatiguing exercise of the knee extensors caused compensatory increases in ankle and hip musculature %MVC to similar extents in both age groups. Lastly, timings of peak muscle activation amplitudes relative to instant of seat-off was invariant of fatigue conditions in both age groups, whereas knee extensors fatigue caused earlier onsets of ankle muscle activity when older adults initiated the STS task, which was not observed in young adult participants.

Knee extensor musculature

It is interesting to note that the fatigue protocols caused increased %MVC of the biarticular RF during subsequent STS trials, while those of the monoarticular VL only increased in preparation for seat-off in comparison to baseline, non-fatigue STS conditions. Since the VL was already near maximally active during the ascending phase (~ 90%MVC) in older adults, it is understandable why VL %MVC could not further increase after knee extensor fatigue; however, this was also observed in the younger participants who had substantially lower activation intensities during the ascending phase of the STS. It is possible that RF activity may have been elevated during the fatigue protocol, allowing the vasti to work at similar levels of intensity during the subsequent STS repetitions. For example, previous investigations have found that during repetitive knee extension, the vasti (lateralis, medialis, and intermedius) are initially more synergistically active, while the biarticular RF increase its contribution to knee extensor torque output as fatigue progresses (Akima et al. 2002; Ebenbichler et al. 1998; Kouzaki et al. 1999; Kellis 1999). Considering this, the increased activation intensities of the RF during both the preparatory and ascending phases of the STS observed in this investigation may have occurred to prevent excessive declines in torque output at the knee. Unfortunately, force output cannot be directly inferred from EMG signals (Hug 2011); therefore, we cannot conclude if increased RF STS intensities observed in this investigation are a result of greater initial fatigue accumulation in the vasti, or increased role in contributing to knee extension during the STS after fatiguing exercise.

Evaluations for quadriceps temporal characteristics relative to seat-off after knee extensor fatigue showed no significant change in VL or RF onsets or peak burst activity time in either age group. Although older adult participants had slightly earlier VL and RF onset times compared to young adults, these differences were not statistically significant. Older adult participants did however have earlier peak activity timings of RF for all STS conditions. Together, these findings suggest that the quadriceps have a set motor strategy in producing sufficient knee extensor net joint moments to ascend from a seated position that is not altered by the accumulation of fatigue (Goulart and Valls-Solé 1999), but seem to differ slightly with aging to compensate for impaired force-generating capabilities.

Hip extensor musculature

For the primary monoarticular hip extensor muscle during the STS task, the GMax, the results of this investigation did not find any age differences in activation levels; however, both young and older adult participants experienced significant increase in GMax %MVCs following knee extensor fatiguing exercise. These findings demonstrate the compensatory involvement of the GMax as a result of knee extensor fatigue; however, this may not be directly related to available force outputs since levels did not differ between young and older participants. Regardless, these results do indicate that a similar shift in movement strategy occurred as a result of knee extensor fatigue in both age groups. Analyses of GMax onset times showed that young adults had earlier activation onsets during the Post-50 STS condition in comparison to pre-fatigue and Post-80 conditions. Since this was not associated with any change in peak activity burst time when knee extensor strength reserves of young adults were reduced by 50%, they may have adopted a different control strategy than older adults by allowing the hip extensors to be in a more active state in preparation for seat-off (Walshe et al. 1998; Van Zandwijk et al. 2000). Similarly, Van Zandwijk et al. (2000) observed that in addition to increased activation intensity, earlier onset of the GMax occurred with maximal vertical jumping compared to sub-maximal jumping efforts in their young adult participants. Since increased preparatory GMax %MVCs during this Post-50 condition was lower than those of the POST-80 but comparable to pre-fatigue baseline STS activities, earlier pre-activity of the GMax exhibited by young adults may have been adopted to improve movement efficiency, thus negating the need to increase its activation intensity in preparation for seat-off when knee extensor torque-generating capabilities were further impaired.

Activity of the BF was also evaluated in this investigation and can be considered as the other "synergist" hip extensor muscle. The BF is a constituent of the biarticular hamstring muscle group that assists the GMax in hip extension, as well as causing opposing knee flexor forces at the knee (Bryanton et al. 2015). Therefore, lower levels of hamstrings activity would represent a more efficient STS muscular control strategy. With knee extensor fatigue, a reduction in BF normalized amplitudes was seen during the preparatory phases in both young and older adults, whereas ascending intensities remained unchanged. Declines were also proportional to the extent to which quadriceps force generation was impaired in both age groups, as lower %MVCs were observed in the Post-50 compared to the Post-80 STS condition. Since no significant fatigue or age main effects were found for BF onsets and peak activity timings, reduced %MVC preparatory activities in the absence of temporal shifting in its activation curve may have been a neural control strategy to reduce the amount of co-activity at the knee occurring prior to seat-off.

Older adults in this investigation had similar preparatory, but statistically higher ascending phase BF average %MVC values than young adults for all STS conditions. Therefore, in addition to higher muscular efforts required to perform common tasks of daily living, older adults demonstrate greater coactivity at the knee (Hortobágyi et al. 2003; Larsen et al. 2008). Larsen et al. (2008) attributed elevated EMG normalized activity of lower extremity musculature and greater thigh antagonist activity in older adult participants, to reduced strength reserves associated with aging. Although the BF is a synergist hip extensor, young and older adults had similar GMax %MVC efforts during all STS conditions; therefore, it is unclear whether older adults may have utilized a more hamstring "dominant" hip extensor muscle strategy and as a result require greater quadriceps efforts to counteract the residual greater opposing hamstring flexor forces at the knee (Bryanton et al. 2015). In contrast, greater quadriceps activity as seen in our older adult participants due to reduced knee extensor strength reserves may have necessitated greater hamstring activity. Elevated co-contraction levels have been suggested to be a compensatory control strategy to increase joint stiffness in the face of impaired neuromuscular function with aging to enhance movement control accuracy and postural stability (DeVita and Hortobagyi 2000; Horak et al. 1989; Kallio et al. 2012; Larsen et al. 2008; Nagai et al. 2013; Shaffer and Harrison 2007) and may have contributed to our age group differences.

Ankle plantar flexor musculature

At the ankle, young and older adults had similar average preparatory and ascending ankle plantar flexor efforts regardless of STS condition. With fatigue, SOL and GAS %MVC values increased in both age groups, but did not differ between Post-80 and Post-50 STS conditions. Similar to the GMax, increased ankle plantar flexor contribution to STS performance was not directly dependent on the extent of force declines induced. In older adults, earlier SOL and GAS onset times occurred once knee extensor strength reserves were reduced by 50% (Post-50 STS condition). The role of the ankle plantar flexors in contributing to STS performance is to promote ankle extension to ascend the body vertically, as well as to slow down body forward displacement and stabilize center of pressure positions about the feet (Dehail et al. 2007; Flanagan and Salem 2008). An earlier activation time of the ankle plantar flexor musculature is suggested by Gross et al. (1998) to represent the older participants attempting to begin generating ankle torques required to reduce horizontal momentum. Since this was not exhibited in the older participants in the current investigation until the Post-50 STS condition, this postural strategy was only required once large amounts of fatigue were accumulated and the force quality was greatly impaired. In addition to reduced force output, peripheral fatigue has also been shown to impair the accuracy of somatosensory input obtained and integrated by the associated musculature, leading to declines in postural stability (Paillard 2012). Although postural analyses were not performed in this investigation, impaired balance capabilities in older adults with knee extensor fatigue may have led to alterations in the ankle musculature control strategy to better regulate body sway (Bryanton and Bilodeau 2016). Furthermore, the older adult group's timings of peak GAS and SOL burst activities also occurred significantly later in the STS ascending phase due to larger compensatory corrective responses to break forward body momentum and prevent their center of pressures from deviating outside of their base of support (Dehail et al. 2007; Kanekar and Aruin 2012; Tucker et al. 2008). Together, age-dependent corrective postural responses observed in this investigation may be attributed to age-related declines in postural control capabilities and requires further investigation.

The findings of this investigation demonstrate that compensatory increases in non-fatigued musculature at the ankle and hip in the healthy young and older adults may have allowed them to successfully perform STS repetition post-fatigue. As a result, the knee extensor fatiguing exercise did not physically impact their ability to achieve the task goals: obtaining a fully extended upright standing position. These observations imply that both healthy young and older adult participants can make adequate alterations in their muscle activation behavior to stand up from a seated position. Although performance may have not been reduced per se, we cannot conclude that the way the STS task was performed did not differ between age groups and fatigue conditions such as movement kinematics were not measured in this investigation. It is expected that increased contributions of musculature about joints distal to the ones being fatigued would result in observable difference in movement strategy due to the large degrees of freedom available for human movement (Savelberg et al. 2007; Yoshioka et al. 2007). Therefore, future research is warranted to relate such alterations in muscle behavior to changes in movement kinematics as a means for screening for reduced force-generating capabilities of the knee extensor musculature in older populations at risk of disability.

The use of normalized EMG measures requires the assumption that maximal EMG amplitudes collected are truly maximal in rested (or fatigued) conditions. This is particularly important when using a single standardized isometric maximal contraction to interpret relative muscular efforts during a dynamic task, as it is uncertain whether the muscle has been truly maximally activated. Therefore, performing an isometric MVC to normalize signal characteristics may not have been sufficient to establish an optimal reference value and should be considered a limitation of this investigation. Moreover, the assumption that muscle activities were similar between both limbs was also required in these investigations, since EMG signals were only collected for the dominant limb during STS testing. Therefore, the potential for limb asymmetries in %MVC, as well as other kinematic and kinetic measures used in our analyses, were not accounted for in this thesis and should be considered in future investigations. Lastly, it could be argued that a limitation of this research in comparing age-dependent STS strategies with and without fatigue is that the older adult participants were inherently in the younger age range and may not be reflective of those experiencing substantial functional declines; this minimized potentially large differences between groups. However, since age main effects were in fact observed for muscular activities, we can confidently conclude that group differences were a consequence of healthy aging in older adults without any observable physical impairment. This age group would have also minimized other confounding effects associated with health issues and impairments that are more prevalent in much older individuals ($\geq$ 80 years of age). Regardless, future research endeavors should consider the evaluations of much older populations to further reveal the role of knee extensor strength reserves in limiting STS performance, as well as how improving such reserves through means of intervention may or may not improve STS capabilities.

In summary, isolated knee extension fatiguing exercise resulted in compensatory muscle strategies through increased contribution of non-fatigued muscles and originally less active ankle plantar flexor (SOL and GAS) and hip extensor (GMax) musculature; however, this appeared to not be dependent on the extent or force declines imposed. For the fatigued musculature itself, greater pre-activity of the quadriceps was an observed strategy to compensate for reduced force-generating capabilities. Finally, in addition to higher thigh (VL, RF and BF) muscular efforts in older adult participants, age differences also existed in temporal characteristics of the ankle plantar flexors with and without the presence of knee extensor fatigue. Considering this, reduced force-generating capabilities of the knee extensor musculature appear to influence the neural movement control strategy when rising from a chair; this was particularly apparent in older adults who had significantly lower knee extensor strengths and compensated for near maximal VL effort levels required to stand up from a seated position. Through understanding how reduced knee extensor force-generating capabilities impact STS muscle strategies in older populations, these results further contribute to the development of effective preventative and/or restorative rehabilitation strategies for functional independence with aging. Furthermore, these findings have clinical implications as they demonstrate that an uneven accumulation of fatigue among lower extremity musculature may result in compensatory muscle strategies before any observable declines in performance.

Author contributions MAB conceptualized the study, carried out the data collection and statistical analyses, and wrote and edited the manuscript. MB participated in the conception and design of the study, provided advice and content expertise, and revised the manuscript. All authors read and approved the final manuscript.

References

Akima H, Foley JM, Prior BM, Dudley GA, Meyer RA (2002) Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. J Appl Physiol 92(2):679–684

Akima H, Takahashi H, Kuno SY, Katsuta S (2004) Coactivation pattern in human quadriceps during isokinetic knee-extension by muscle functional MRI. Eur J Appl Physiol 91(1):7–14

Avin KG, Law LA (2011) Age-related differences in muscle fatigue vary by contraction type: a meta-analysis. Phys Ther 91(8):1153–1165

Bassey EJ, Fiatrone MA, O'Neill EF, Kelly M, Evans WJ, Lipsitz LA (1992) Leg extensor power and functional performance in very old men and women. Clin Sci 82:321–327

Bieryla KA, Anderson DE, Madigan ML (2009) Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity. J Electromyogr Kinesiol 19(1):139–144

Bilodeau M, Henderson TK, Nolta BE, Pursley PJ, Sandfort GL (2001) Effect of aging on fatigue characteristics of elbow flexor muscles during sustained submaximal contraction. J Appl Physiol 91(6):2654–2664

Bohannon RW (2009) Body weight-normalized knee extension strength explains sit-to-stand independence: a validation study. J Strength Cond Res 23(1):309–311

Bonnard M, Sirin AV, Oddsson L, Thorstensson A (1994) Different strategies to compensate for the effects of fatigue revealed by neuromuscular adaptation processes in humans. Neurosci Lett 166(1):101–105

Brech GC, Alonso AC, Luna NMS, Greve JM (2013) Correlation of postural balance and knee muscle strength in the sit-to-stand test among women with and without postmenopausal osteoporosis. Osteoporos Int 24(7):2007–2013

Bryanton MA, Bilodeau M (2016) Postural stability with exhaustive repetitive sit-to-stand exercise in young adults. Hum Mov Sci 49:47–53

Bryanton MA, Carey JP, Kennedy MD, Chiu LZ (2015) Quadriceps effort during squat exercise depends on hip extensor muscle strategy. Sports Biomech 14(1):122–138

Burnfield JM, Shu Y, Buster TW, Taylor AP, McBride MM, Krause ME (2012) Kinematic and electromyographic analyses of normal and device-assisted sit-to-stand transfers. Gait Posture 36(3):516–522

Carville SF, Perry MC, Rutherford OM, Smith ICH, Newham DJ (2007) Steadiness of quadriceps contractions in young and older adults with and without history of falling. Eur J Appl Physiol 100:527–533

Chiu LZ, Bryanton MA, Moolyk AN (2012) Proximal-to-distal sequencing in vertical jumping with and without arm swing. J Strength Cond Res 28(5):1195–1202

Corrigan D, Bohannon RW (2001) Relationship between knee extension force and stand-up performance in community-dwelling elderly women. Arch Phys Med Rehabil 82(12):1666–1672
Dehail P, Bestaven E, Muller F, Mallet A, Robert B, Bourdel-Marchasson I, Petit J (2007) Kinematic and electromyographic analysis of rising from a chair during a "Sit-to-Walk" task in elderly subjects: role of strength. Clin Biomech 22(10):1096–1103
DeVita P, Hortobagyi T (2000) Age causes a redistribution of joint torques and powers during gait. J Appl Physiol 88(5):1804–1811
Ebenbichler G, Kollmitzer J, Quittan M, Uhl F, Kirtley C, Fialka V (1998) EMG fatigue patterns accompanying isometric fatiguing knee-extensions are different in mono-and bi-articular muscles. Electroencephalogr Clin Neurophysiol Electromyogr Motor Control 109(3):256–262
Eriksrud O, Bohannon RW (2003) Relationship of knee extension force to independence in sit-to-stand performance in patients receiving acute rehabilitation. Phys Ther 83(6):544–551
Flanagan SP, Salem GJ (2008) Lower extremity joint kinetic responses to external resistance variations. J Appl Biomech 24(1):58
Fujita E, Kanehisa H, Yoshitake YA, Fukunaga T, Nishizono H (2011) Association between knee extensor strength and EMG activities during squat movement. Med Sci Sports Exerc 43(12):2328–2334
Godin G, Shepard RJ (1997) Godin and Leisure-Time Exercise Questionnaire. Med Sci Sports Exerc 29:S36–S38
Goulart FRDP, Valls-Solé J (1999) Patterned electromyographic activity in the sit-to-stand movement. Clin Neurophysiol 110(9):1634–1640
Gregoire L, Veeger HE, Huijing PA, van Ingen SG (1984) Role of mono-and biarticular muscles in explosive movements. Int J Sports Med 5(6):301–305
Gross MM, Stevenson PJ, Charette SL, Pyka G, Marcus R (1998) Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. Gait Posture 8(3):175–185
Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg G (1999) European recommendations for surface electromyography. Roessingh Res Dev 8(2):13–54
Horak FB, Shupert CL, Mirka A (1989) Components of postural dyscontrol in the elderly: a review. Neurobiol Aging 10(6):727–738
Hortobágyi T, Mizelle C, Beam S, DeVita P (2003) Old adults perform activities of daily living near their maximal capabilities. J Gerontol Ser A Biol Sci Med Sci 58(5):M453–M460
Hug F (2011) Can muscle coordination be precisely studied by surface electromyography? J Electromyogr Kinesiol 21(1):1–12
Hughes MA, Myers BS, Schenkman ML (1996) The role of strength in rising from a chair in the functionally impaired elderly. J Biomech 29(12):1509–1513
Hunter SK, Critchlow A, Enoka RM (2004) Influence of aging on sex differences in muscle fatigability. J Appl Physiol 97(5):1723–1732
Kallio J, Sogaard K, Avela J, Komi P, Selanne H, Linnamo V (2012) Age-related decreases in motor unit discharge rate and force control during isometric plantar flexion. J Electromyogr Kinesiol 22(6):983–989
Kanekar N, Aruin AS (2012) Aging and balance control in response to external perturbations: role of anticipatory and compensatory postural mechanisms. Age 36(3):1067–1077
Kellis E (1999) The effects of fatigue on the resultant joint moment, agonist and antagonist electromyographic activity at different angles during dynamic knee extension efforts. J Electromyogr Kinesiol 9(3):191–199
Kent-Braun JA, Ng AV (1999) Specific strength and voluntary muscle activation in young and elderly women and men. J Appl Physiol 87(1):22–29
Kouzaki M, Shinohara M, Fukunaga T (1999) Non-uniform mechanical activity of quadriceps muscle during fatigue by repeated maximal voluntary contraction in humans. Eur J Appl Physiol 80(1):9–15
Ikezoe T, Mori N, Nakamura M, Ichihashi N (2011) Atrophy of the lower limbs in elderly women: Is it related to walking ability? Eur J Appl Physiol 111:989–995
Larsen AH, Puggaard L, Hämäläinen U, Aagaard P (2008) Comparison of ground reaction forces and antagonist muscle coactivation during stair walking with ageing. J Electromyogr Kinesiol 18(4):568–580
LeRoche DP, Cromin KA, Greenleaf B, Croce RV (2010) Rapid torque development in older female fallers and non-fallers: a comparison across lower-extremity muscles. J Electromyogr Kinesiol 20:482–488
Muhlberg W, Sieber C (2004) Sarcopenia and frailty in geriatric patients: Implications or training and prevention. Z Gerontol Geriatr 37:2–8
Nagai K, Yamada M, Mori S, Tanaka B, Yemura K, Aoyama T, Ichihashi N, Tsuboyama T (2013) Effect of the muscle coactivation during quiet standing on dynamic postural control in older adults. Arch Gerontol Geriatr 56(1):129–133
Paillard T (2012) Effects of general and local fatigue on postural control: a review. Neurosci Biobehav Rev 36(1):162–176
Petrella JK, Kim JS, Tuggle SC, Hall SR, Bamman MM (2005) Age differences in knee extension power, contractile velocity, and fatigability. J Appl Physiol 98(1):211–220
Puniello MS, McGibbon CA, Krebs DE (2001) Lifting strategy and stability in strength-impaired elders. Spine 26(7):731–737
Renshaw D, Bice MR, Cassidy C, Eldridge JA (2010) A comparison of three computer-based methods used to determine EMG signal amplitude. Int J Exerc Sci 3(1):43–48
Roos MR, Rice CL, Vandervoort AA (1997) Age-related changes in motor unit function. Muscle Nerve 20:679–690
Savelberg HHCM, Fastenau A, Willems PJB, Meijer K (2007) The load/capacity ratio affects the sit-to-stand movement strategy. Clin Biomech 22(7):805–812
Shaffer SW, Harrison AL (2007) Aging of the somatosensory system: a translational perspective. Phys Ther 87(2):193–207
Tucker MG, Kavanagh JJ, Barrett RS, Morrison S (2008) Age-related differences in postural reaction time and coordination during voluntary sway movements. Hum Mov Sci 27(5):728–737
Van Zandwijk JP, Bobbert MF, Munneke M, Pas P (2000) Control of maximal and submaximal vertical jumps. Med Sci Sports Exerc 32(2):477–485
Van Roie E, Verschueren SM, Boonen S, Bogaerts A, Kennis E, Coudyzer W, Delecluse C (2011) Force-velocity characteristics of the knee extensors: an indication of the risk for physical frailty in elderly women. Arch Phys Med Rehabil 92(11):1827–1832
Van der Heijden MM, Meijer K, Willems PJ, Savelberg HH (2009) Muscles limiting the sit-to-stand movement: an experimental simulation of muscle weakness. Gait Posture 30(1):110–114
Vigotsky AD, Harper EN, Ryan DR, Contreras B (2015) Effects of load on good morning kinematics and EMG activity. PeerJ. 3:e708
Walshe AD, Wilson GJ, Ettema GJ (1998) Stretch-shorten cycle compared with isometric preload: contributions to enhanced muscular performance. J Appl Physiol 84(1):97–106
Wretenberg P, Arborelius UP (1994) Power and work produced in different leg muscle groups when rising from a chair. Eur J Appl Physiol 68(5):413–417
Yoshioka S, Nagano A, Himeno R, Fukashiro S (2007) Computation of the kinematics and the minimum peak joint moments of sit-to-stand movements. Biomed Eng Online 6(1):26