Archives of Gerontology and Geriatrics 57 (2013) 192–197

Contents lists available at SciVerse ScienceDirect

Archives of Gerontology and Geriatrics

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

The functional demand (FD) placed on the knee and hip of older adults during everyday activities

Dinesh Samuel [a,*], Philip Rowe [b], Alexander Nicol [b]

[a] Faculty of Health Sciences, University of Southampton, UK
[b] Bioengineering Unit, University of Strathclyde, Glasgow, UK

ARTICLE INFO

Article history:
Received 24 October 2012
Received in revised form 1 March 2013
Accepted 7 March 2013
Available online 2 April 2013

Keywords:
FD
Gait
CR
CSt
Stair negotiation
Muscle strength
Joint moment

ABSTRACT

Age-related decline in physical capacity and diminishing physiological reserves may increase the demand placed on lower extremity joints during everyday activities. This study aimed to characterize the FD at the knee and hip joints of older adults during various mobility activities. Eighty-four healthy participants (60–88 years) performed strength tests using a custom-built dynamometer. Biomechanical assessment of gait, chair rise (CR) and sit-down (CSt), stair ascent (SA) and descent (SD) was performed using an 8-camera VICON system (120 Hz) and Kistler force plates. Comparisons between groups (60s, 70s and 80s) were made using ANOVA. The FD was defined as the muscle moment generated during a task, divided by the maximum isometric strength (expressed as a percentage). FD was higher in the 80s age group compared to those in the 60s. The demand on hip and knee extensors was normally higher than those of flexors across all the activities. The knee extensor demand during gait (101%), SA (103%) and SD (120%), and hip extensor demand during gait (127%) were high requiring moments in excess of the maximum isometric muscle strength available at these joints. FD during CR and CSt was comparatively lower with knee extensor demands of 73% and 69% and hip extensor demands of 88% and 51%, respectively. Gait, SA and SD placed high demands on the knee extensors while hip extensor demand was high for gait, CR, CSt and SA. The levels of demand leave little reserve capacity for the older adult to draw on in unexpected circumstances.

1. Introduction

Muscle function is an important determinant of physical performance as the joint moments produced by muscles control the external moments generated during everyday activities. Walking is a critical functional activity for mobility, is important for maintaining health and function, and is essential for performance of many activities of daily living (Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998; Prince, Corriveau, Herbert, & Winter, 1997). Abnormal gait is predictive of falls and institutionalization (Verghese et al., 2002) and early identification of gait impairment might help identify older adults who are at risk of functional limitation, falls and injuries (Verghese et al., 2006). Similarly, rising from a chair is a precursor to several mobility activities including walking and is important for independent living (Hughes, Weiner, Schenkman, Long, & Studenski, 1994; Ikeda, Schenkman, Riley, & Hodge, 1991; Laporte, Chan, & Sveistrup, 1999; Rodosky, Andriacchi, & Andersson, 1989). When compared to CR, the CSt phase has received little attention (Durward, Baer, & Rowe, 1999; Kerr, White, Barr, & Mollan, 1997). Among mobility-based tasks, stair negotiation is a physically challenging activity and peak knee flexion moments during SA have been reported to be three times greater than those of level walking (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; Startzell, Owens, Mulfinger, & Cavanagh, 2000). Stairs pose a serious falls risk to older people with over 60% of accidents occurring on stairs (DTI, 2010). Diminishing physiological reserves and a decline in physical capacity with increasing age predispose the older person to an increased risk of falls. Biomechanical analysis aimed at evaluating the demand placed on lower extremity joints during everyday activities could enhance our understanding of the requirements of various tasks and help inform development of suitable clinical interventions to address functional deficits. In addition, profiles of "FD" generated by different daily living tasks is of interest to clinicians, bioengineers, patients and their carers so as to set targets for rehabilitation (Macdonald et al., 2007). To date, few studies have evaluated the biomechanical demand placed on lower extremity muscles and joints and these have involved small sample sizes

* Corresponding author at: Faculty of Health Sciences, Building 45, Burgess Road, University of Southampton, Southampton SO17 1BJ, UK. Tel.: +44 02380 598925; fax: +44 02380 595301.
E-mail address: D.Samuel@soton.ac.uk (D. Samuel).

0167-4943/$ – see front matter © 2013 Elsevier Ireland Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.archger.2013.03.003

with a limited range of activities being investigated (Costigan, Deluzio, & Wyss, 2002; Livingston, Stevenson, & Olney, 1991; McFadyen & Winter, 1988; Protopapadaki, Drechsler, Cramp, Coutts, & Scott, 2007). Previous investigations (Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2006; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008) have suggested that older adults operated at a higher proportion of their maximum capacity when compared to young adults with a high loading placed on knee and ankle joints during stair negotiation (Hortobágyi, Mizelle, Beam, & DeVita, 2003; Reeves et al., 2006; Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Magnaris, 2009). While earlier biomechanical studies have highlighted a range of issues relating to task performance, these have involved small participant numbers ranging between 5 and 23 older adults and hence have limited inferential ability (Alexander, Schultz, & Warwick, 1991; Hughes, Myers, & Schenkman, 1996; Mourey, Pozzo, Rouhier-Marcer, & Didier, 1998; Schenkman, Berger, Riley, Mann, & Hodge, 1990; Schultz, 1992). Furthermore no previous studies have looked at the age-related decline in performance and biomechanical demand during a variety of functional activities in the same population of healthy older adults of different age groups.

The FD is dependant on the external moments developed by gravity and inertia at each of the joints and the internal moments required to be produced by the muscles crossing that joint in order to counteract the external moment generated during a functional task (Samuel, Rowe, Hood, & Nicol, 2011). Conventionally, the loading on the muscle group has been evaluated by comparing the peak external moment in a functional task with the maximum muscle strength. However this method is flawed because the peak external moment may occur at a joint angle different to the position of maximal muscle strength and muscle strength is highly dependent on joint angle (Samuel & Rowe, 2009). Hence, in this study we defined "FD" as the muscle moment required at a particular joint angle during a functional task, divided by the maximum isometric muscle strength available at the joint angle (expressed as a percentage) (Rowe, Samuel, & Hood, 2005). Therefore, the aim of the present study was to characterize the level of FD placed on the hip and knee joints during gait, CR, CSt and SA and SD in older adults.

2. Methods

Ethical approval was obtained from the Ethics Committee of the Bioengineering Unit, University of Strathclyde. All participants provided written informed consent prior to participation in the study.

2.1. Participants

Eighty-four healthy older adults aged 60–88 years (mean age 73.2 years (SD 7.3); height 1.66 m (SD 0.1); body mass 73.7 kg (SD 13.1)); 41 males and 43 females were recruited through posters placed in older adult organizations in the Greater Glasgow area, Stirlingshire and Ayrshire in Scotland, UK. Participants were categorized into three sub-groups (60–69 years, 70–79 years and 80 years and over) based on their age and were from a wide range of social, economic and educational backgrounds as reported through an initial screening questionnaire. The inclusion and exclusion criteria published previously (Greig et al., 1994) were adopted for inclusion of older adults. Those with neurological conditions, musculoskeletal disease or systemic disorders affecting multiple joints such as Rheumatoid Arthritis were excluded from the study. Participants attended the Biomechanics Laboratory at the University of Strathclyde for two, 2-h sessions, one for muscle strength tests and one for whole body biomechanical assessment.

2.2. Equipment and protocol

2.2.1. Muscle strength measurements

A torque dynamometer attached to a purpose-built plinth was utilized to measure isometric muscle moments. The device consisted of a strain-gauged metal bar referred to as the transducer attached to a circular indexing wheel. The transducer and indexing wheel were attached to an aluminum base which was secured to the frame of a custom-built plinth. The output from the transducer was amplified using a strain-gauge amplifier and was input into a 16-channel analog to digital data collection system, housed inside a PC computer. A turbo Pascal computer program was used to collect the data. The signal from the strain-gauged transducer was sampled at a frequency of 50 Hz. Details of the equipment utilized for testing lower extremity strength has been presented elsewhere (Samuel & Rowe, 2009). The dynamometer was accurate to <1 Nm and precise to 0.1 Nm within the measuring range of 300 Nm. The isometric strength measurements were found to be repeatable with intra-class correlation coefficients ranging from 0.79 to 0.96 for the knee and 0.84–0.95 for the hip muscles.

Muscle strength was tested through joint range for knee extensors and flexors (at 90°, 60°, and 20° of knee flexion) and hip extensors and flexors (at 45°, 30°, and 0° of hip flexion). The joint angles were chosen to reflect the lengthened, mid and shortened positions of muscle action for the respective muscle groups. As a first approximation, muscle strength was assumed to vary linearly between data points. However, in reality the curve will be polynomial but given the limited number of joint positions tested only a linear interpolation was possible. The test positions were standardized and an upper body harness system along with a pelvic strap were utilized to isolate force measures to the individual muscle groups tested. Maximal isometric contractions were held for 3 s each, with a 30-s rest period between consecutive contractions. A sub-maximal practice trial was performed prior to actual testing and instructions provided to participants were standardized. Strong verbal encouragement using standardized instructions to motivate participants to produce a maximal contraction, and visual feedback through real-time display of their isometric effort on a computer monitor was provided. The maximum value from two trials was used in the analysis. The sign convention adopted was that flexion moments were positive and extension moments were negative. Body mass and height were measured using metric equipment.

2.2.2. Biomechanical analysis

A full body 3-D biomechanical assessment was carried out during functional activities (gait, CR, CSt, SA and SD) using a VICON® (Vicon v 4.4; Oxford Metrics, UK) 8-camera motion analysis system (120 Hz) with 3 Kistler forceplates (1080 Hz). A standard height chair (460 mm) and a custom-built four-step instrumented stairway (step height – 185 mm; depth – 280 mm) with hand rails were utilized. A full body marker placement protocol was developed to enable identification of bony landmarks whilst minimizing artifacts caused by soft tissue movement. The participants wore tight lycra body suits and normal shoes during the tests. 14 mm reflective markers were attached using double-sided wig tape to the bony landmarks. Individual markers were attached bilaterally to the ASIS, PSIS, medial/lateral epicondyles of femur, medial/lateral malleoli, C7 spine, T8, jugular notch, ziphysternum, proximal/distal 3rd metacarpal, distal 5th metacarpal, ball of big toe, 5th metatarsal and mid heel. In addition, cluster of markers (4 markers) were attached to cuffs placed on the upper arm, forearm, thigh and lower leg bilaterally. Participants performed three practice sessions at a self-selected speed and data were captured for three subsequent repetitions of each activity.

Three trials were performed and the average of the three was taken. The trials were labeled manually and processed using a purpose written program in Vicon Body builder software. The data were output as ASCII files and imported into Excel for further analysis. A purpose written program in Excel was used to amalgamate the data on the knee and hip angles and moments produced during the above functional activities.

The muscle strength data were combined with the biomechanical moment and angle data to determine the "FD" placed on the muscles during stair negotiation. FD for a muscle group was defined as the muscle moment required at a particular joint angle, divided by the maximum isometric muscle strength available at that joint angle (expressed as a percentage). In other words the functional moment occurring at a particular position in the joint range was compared with the muscle strength obtained from muscle tests performed at the same position within the joint range. FD was therefore calculated on an instant-to-instant basis for the joint and using the relevant muscle strength for that joint at that angle. A linear interpolation was used to estimate joint strength between the muscle test angles as a first approximation. Ideally, it would have been helpful to have measured isometric strength at a greater number of joint positions in order to have a more continuous strength curve. However, we were limited to three positions in order to minimize the effect of fatigue. FD was calculated throughout the movement as the ratio of the moment produced during a functional activity (the moment required to carry out the movement, the demand) to the actual available isometric muscle strength for the respective muscle group at that angle (the participant's maximum moment generating capacity). For example, if the knee required to produce a moment (estimated from the biomechanical analysis) of 50 Nm at an angle of 45° and our muscle strength data indicated their maximum isometric strength at this angle was 100 Nm then the FD would be 50%. If the demand and capacity were equal then the FD would be 100% and if the demand outstripped the capacity then the FD would exceed 100% of the maximal isometric strength at that angle. This is possible during eccentric and concentric contractions where the literature indicates that these may exceed isometric strength by 15–25%.

2.3. Statistical analysis

Descriptive statistics were computed and analysis was carried out using SPSS version 16. Data were examined for normality using the Shapiro–Wilks test and were found to be normally distributed. Comparisons between groups were made using analysis of variance. Statistical significance was set at $p < 0.05$. Data were expressed as means and standard deviations (SD) in the text and tables.

3. Results

3.1. Muscle strength

Maximal isometric hip and knee moments measured at various joint angles declined with increasing age and participants in their 80s had 76–84% of the strength of those who were in their 60s. The detailed results from maximal isometric strength tests have been reported in an earlier publication (Samuel & Rowe, 2009). The mean peak knee muscle moments at 20°, 60° and 90° of knee flexion were 55.6 Nm, 53.1 Nm, 46.3 Nm for flexors and −53.9 Nm, −97.8 Nm, −94.2 Nm for extensors respectively. The mean peak hip muscle moments at 0°, 30° and 45° of hip flexion were 90.4 Nm, 84.6 Nm, 76.6 Nm for flexors and −47.3 Nm, −69 Nm, −71.4 Nm for extensors respectively (Samuel & Rowe, 2009).

3.2. FD

The FD data is presented for the cohort as a whole for each activity cycle for gait, CR and CSt incorporating both flexor (positive) and extensor (negative) demands in Fig. 1 Knee and Fig. 2 Hip. The FD profile during stair negotiation cycle has been presented elsewhere (Samuel et al., 2011). The maximal FDs for the three age groups during the five tasks are reported in Table 1. The FD for older adults in the 80s age group was normally higher than those in the 60s and the difference in FD of 80-year-old participants ranged from 75 to 155 percent of that of the 60-year-olds. Age cohort-wise difference was not statistically significant however, an increasing trend was noticed in the overall FDs with increasing age particularly in the following measures, Gait – knee flexors, knee extensors, hip extensors; CR – knee extensors, hip extensors; CSt – knee extensors, hip extensors; SA – knee extensors, hip extensors; SD – knee flexors, knee extensors, hip flexors and hip extensors.

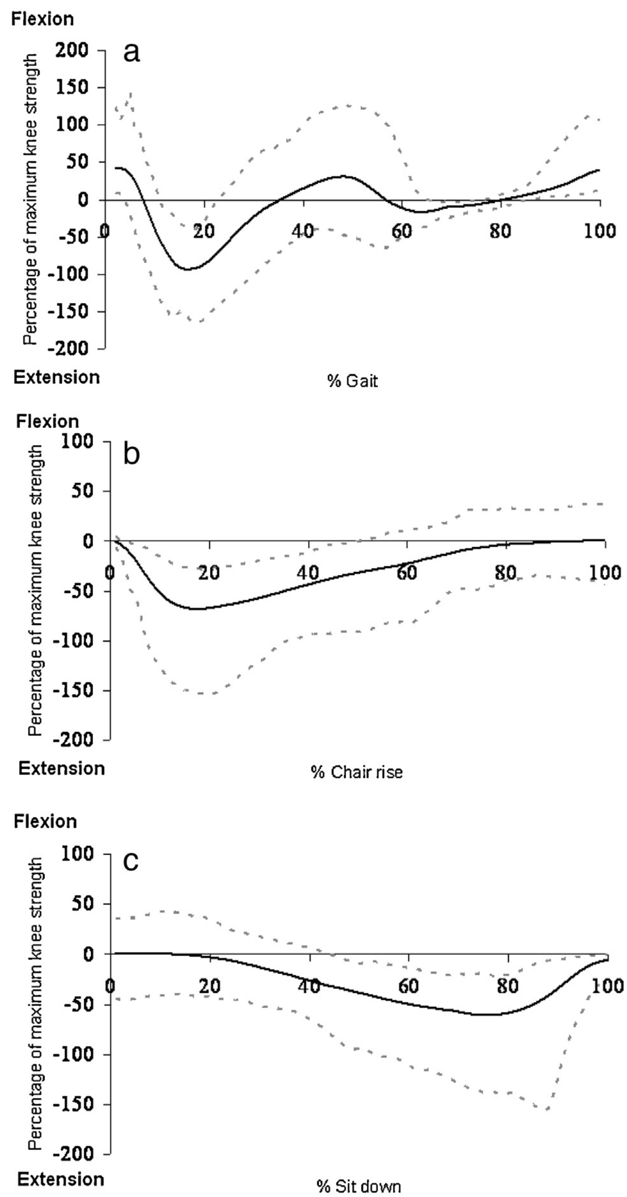

Fig. 1. Mean, 2.5th and 97.5th percentiles of FD for knee joint during Gait, CR and CSt in older adults ($n = 84$) – (a) knee joint – gait (b) knee joint – CR (c) knee joint – CSt.

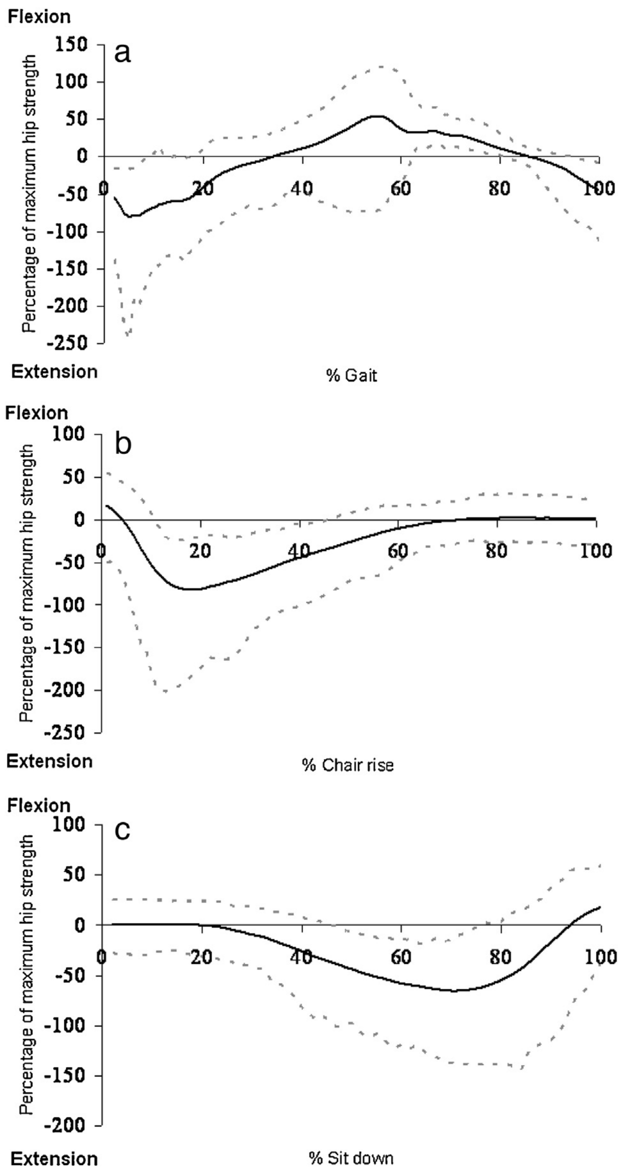

Fig. 2. Mean, 2.5th and 97.5th percentiles of FD for hip joint during Gait, CR and CSt in older adults (n = 84) – (a) hip joint – gait (b) hip joint – CR (c) hip joint – CSt.

The FD on the extensors of hip and knee joints was normally higher than those of flexors across all the activities. For knee extensors, the overall FD values ranged from 69% for CSt to 120% for SD. The overall FD of hip extensors ranged from 51% for SD to 127% during gait. The knee extensor demand during gait (101%), SA (103%) and SD (120%); and hip extensor demand during gait (127%) were in excess of the maximum isometric muscle strength available. This is possible in eccentric and concentric modalities where more than maximum voluntary isometric strength can be elicited. The demand on knee flexors was high for gait (75%) and SD (73%) while a slightly lower hip flexor demand was noticed during gait (68%).

4. Discussion

The present study has provided a comprehensive analysis of FD at the knee and hip joints during everyday functional tasks measured on a large sample of older adults in three age groups. The findings of this study are unique as no previous study has investigated FDs on the knee and hip joints during a number of mobility-based activities. In addition, our data enhances our understanding of physical performance of older adults in terms of the FDs encountered at the knee and hip joints during everyday activities.

The functional tasks that were found to be most demanding were gait, SA and SD. The FD on the knee and hip muscles were relatively high for gait, which one would perhaps consider a simple task and the least demanding. The joint moments generated during functional activities did not change with increasing age. The requirements of the tasks may remain the same and this is reflected in the lack of change in joint moments across the three age groups of older adults.

During CR, carried out with a standard height chair (460 mm) the mean knee extensor demand was 72.8% and the hip extensor demand was 88.2%. High knee extensor relative effort reaching maximal capacity has been reported for older adults while performing a sit to stand task (Hortobágyi et al., 2003; Hughes et al., 1996). The present study also investigated the stand-to-sit phase and our findings suggest that CSt is equally demanding producing high extensor demands on knee (69%) and hip (74%) joints of older adults. In contrast the knee flexor and hip flexor demands during CR and CSt were low and did not appear to pose a problem. The results from the current study demonstrate that rising from a chair and sitting down are particularly demanding tasks for the older adults requiring a higher percentage of knee extensor and hip extensor muscle strength to perform the activity.

Stair negotiation placed a high level of demand on the knee extensors with demand in SA reaching isometric capacity (103%) and during the eccentric phase of SD exceeding it by 20% (120%). Hip extensor demand was high during SA (89%) and the knee flexors also experienced a high level of demand during SD. The FD of knee extensors was higher during SD than SA. Hip flexor demands were relatively low for both SA (42.7) and SD (43.3) while knee flexor demand was higher for SD (73.3) compared to SA (42.2). Hence, SA placed a high demand on the knee extensors and hip extensors with relatively low demand on knee flexors and hip flexors. On the other hand, SD was found to be more demanding on the knee extensors and knee flexors than SA. The FD for both SA and SD were higher in the present study compared to the relative effort values reported previously (Hortobágyi et al., 2003; Reeves et al., 2008, 2009). The demand values in the present study were higher for both activities than those reported earlier (Reeves et al., 2008, 2009), where concentric and eccentric muscle strength was used to assess maximal capabilities at the knee and ankle joint. The higher FD values noted in the current study could be explained by differences in the method adopted for assessing maximal muscle strength. Our muscle strength values were obtained through isometric tests which is likely to reduce the maximal joint moments used in the divisor of the FD ratio for activities involving eccentric muscle activity, therefore increasing the relative effort or FD at each point in time. Also we used isometric strength through joint range rather than the peak point in the range. It will tend to reduce the isometric strength available and hence lead to larger FD values as was the case. The peak moment developed across the range will over estimate the strength available at all points in the range other than the angle at which the peak moment is generated. We consider our approach which takes into account the length-tension relationship of the muscle to be more representative and to have greater content validity.

It should be noted that the knee extensors will be contracting eccentrically during the lowering phase of CSt and SD to control the movement as opposed to a isometric contraction. Eccentric strength was not measured in the current study and hence FD was computed using isometric strength. As isometric strength is lower than eccentric strength it is possible for the FD as calculated to exceed 100% overestimated. In addition, eccentric muscle

Table 1
FD at hip and knee joints during gait, CR, CSt, SA and SD for three age groups of older adults. Data are presented as means (SD). There were no statistically significant effects of age group on any of the outcomes.

	All subjects			Overall
	60–69 years ($n = 30$)	70–79 years ($n = 30$)	80 and above ($n = 24$)	($n = 84$)
Gait				
Knee extensor demand (%)	−94.7 (39)	−92.2 (32.7)	−120.4 (32.3)	−101.1 (36.6)
Knee flexor demand (%)	75.4 (47.6)	71.2 (30)	80 (52.3)	75.2 (43.1)
Hip extensor demand (%)	−113.5 (57.7)	−123.8 (50.6)	−150.4 (68.7)	−127 (59.4)
Hip flexor demand (%)	61.5 (28.4)	75.6 (31.9)	67.4 (14.9)	68.1 (27.3)
CR				
Knee extensor demand (%)	−72 (36.9)	−67.4 (28.8)	−81.9 (41.2)	−72.8 (35.3)
Knee flexor demand (%)	9.8 (13.8)	11.3 (12)	9.3 (11.2)	10.2 (12.4)
Hip extensor demand (%)	−84.5 (48.2)	−87.6 (35.8)	−94.7 (35.8)	−88.2 (40.8)
Hip flexor demand (%)	22.5 (12.2)	21.3 (13.6)	21.6 (19.8)	21.8 (14.7)
CSt				
Knee extensor demand (%)	−66.2 (33.5)	−66.1 (30.7)	−78.5 (39.2)	−69.2 (34)
Knee flexor demand (%)	9 (14.5)	7.6 (14.1)	8 (14.5)	8.3 (14.2)
Hip extensor demand (%)	−72.4 (41.4)	−70.7 (31.1)	−80 (33.6)	−73.7 (35.8)
Hip flexor demand (%)	24.9 (18)	23.3 (14)	21.4 (17.3)	23.5 (16.3)
SA				
Knee extensor demand (%)	−90.5 (25.7)	−95.4 (25.6)	−126 (53.9)	−102.9 (39.1)
Knee flexor demand (%)	39.7 (14.5)	44 (18.6)	43.2 (15.7)	42.2 (16.1)
Hip extensor demand (%)	−78.3 (37.2)	−96 (53.1)	−96.4 (29.8)	−88.9 (41.2)
Hip flexor demand (%)	39.2 (16.8)	47.8 (25.7)	42 (13.1)	42.7 (19.3)
SD				
Knee extensor demand (%)	−115.6 (40.2)	−111 (37.1)	−138.3 (54.4)	−120.4 (44.6)
Knee flexor demand (%)	70.2 (46.3)	69.1 (29.6)	82.6 (66.9)	73.3 (48.2)
Hip extensor demand (%)	−48.5 (36.9)	−48.2 (36.2)	−57.7 (30.9)	−50.6 (35)
Hip flexor demand (%)	44.4 (18.7)	48.9 (51.8)	33.6 (10.5)	43.3 (32.2)

strength has been observed to be relatively preserved in old age and does not show the same degree of decline with advancing age as noted with isometric and concentric muscle strengths (Lindle et al., 1997; Vandervoort, Kramer, & Wharram, 1990). Hortobágyi et al. (2003) observed that an increased FD in older adults was associated with an increased neural drive to the involved muscle and an increased coactivity of antagonist muscles. It is possible that the increased muscle coactivation is due to the demanding nature of the tasks and that antagonistic action may exacerbate the situation further. What is striking from the data is that these everyday tasks pushed our participants to their maximal limits and in some cases over their isometric limit. SD was particularly demanding giving an FD of 120% at the knee for extensor group. This is possible as eccentric muscle strength can be approximately 20% greater than that measured isometrically. However the participants were clearly at their functional capacity descending stairs.

5. Conclusions

In conclusion, analysis of FD during everyday activities was carried out in detail taking into account age and gender-based differences on a large sample of older adults. The FD on the knee and hip muscles increased with advancing age and the oldest group had the highest knee extensor and hip extensor demand. The published data on functional activities is lacking in information on older adults who are over 80 years in age and muscle strength is shown to decline as people age with those in their 80s having the lowest strengths. Therefore, the FD values obtained in this study were found to be higher than those that have reported relative effort on a younger sample of older adults. The loss of muscle strength with advancing age might lead to an increase in the FD of performing simple everyday activities. The high demands could result in the older adult loosing the ability to perform these every day tasks safely. Furthermore, the physical challenge on the declining musculoskeletal system of the older adult could increase the risk associated with the tasks resulting in falls and injury.

Conflict of interest statement

None declared.

Acknowledgements

The authors wish to thank the participants who took part in the study, Victoria Hood for carrying out biomechanical analysis, Dave Robb and John Maclean, Bioengineering Unit, University of Strathclyde for technical assistance. This work was supported by the Engineering and Physical Sciences Research Council Extending Quality of Life Grant [GR/R2 6856/01], United Kingdom.

References

Alexander, N. B., Schultz, A. B., & Warwick, D. N. (1991). Rising from a chair: Effects of age and functional ability on performance biomechanics. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 46*, 91–98.

Andriacchi, T. P., Andersson, G. B., Fermier, R. W., Stern, D., & Galante, J. O. (1980). A study of lower-limb mechanics during stair-climbing. *Journal of Bone and Joint Surgery, 62*, 749–757.

Costigan, P. A., Deluzio, K. J., & Wyss, U. P. (2002). Knee and hip kinetics during normal stair climbing. *Gait and Posture, 16*, 31–37.

Department of Trade and Industry (DTI). Avoiding slips, trips and broken hips: Falls on stairs in the home involving older people. (Online). Available at www.dti.gov.uk/homesafetynetwork/pdffalls/stats2.pdf Accessed 09.2010.

Durward, B. R., Baer, G. D., & Rowe, P. J. (1999). *Functional human movement: Measurement and analysis.* Oxford: Butterworth-Heinemann.

Greig, C. A., Young, A., Skelton, D. A., Pippet, E., Butler, F. M. M., & Mahmud, S. M. (1994). Exercise studies with elderly volunteers. *Age and Ageing, 23*, 85–89.

Hortobágyi, T., Mizelle, C., Beam, S., & DeVita, P. (2003). Old adults perform activities of daily living near their maximal capabilities. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 58*, 453–460.

Hughes, M. A., Myers, B. S., & Schenkman, M. L. (1996). The role of strength in rising from a chair in the functionally impaired elderly. *Journal of Biomechanics, 29*, 1509–1513.

Hughes, M. A., Weiner, D. K., Schenkman, M. L., Long, R. M., & Studenski, S. A. (1994). Chair rise strategies in the elderly. *Clinical Biomechanics, 9*, 187–192.

Ikeda, E. R., Schenkman, M. L., Riley, P. O., & Hodge, W. A. (1991). Influence of age on dynamics of rising from a chair. *Physical Therapy, 71*, 473–481.

Kerr, K. M., White, J. A., Barr, D. A., & Mollan, R. A. B. (1997). Analysis of the sit-stand-sit movement cycle in normal subjects. *Clinical Biomechanics, 12*, 236–245.

Kerrigan, D. C., Todd, M. K., Della Croce, U., Lipsitz, L. A., & Collins, J. J. (1998). Biomechanical gait alterations independent of speed in the healthy elderly: Evidence for specific limiting impairments. *Archives of Physical Medicine and Rehabilitation, 79*, 317–322.

Laporte, D. M., Chan, D., & Sveistrup, H. (1999). Rising from sitting in elderly people, part 1: Implications of biomechanics and physiology. *British Journal of Occupational Therapy, 62*, 36–42.

Lindle, R. S., Metter, E. J., Lynch, N. A., Fleg, J. L., Fozard, J. L., Tobin, J., et al. (1997). Age and gender comparisons of muscle strength in 654 women and men aged 20–93 yr. *Journal of Applied Physiology, 83*, 1581–1587.

Livingston, L. A., Stevenson, J. M., & Olney, S. J. (1991). Stair climbing kinematics on stairs of differing dimensions. *Archives of Physical Medicine and Rehabilitation, 72*, 398–402.

Macdonald, A. S., Loudon, D., Rowe, P. J., Samuel, D., Hood, V., Nicol, A. C., et al. (2007). Towards a design tool for visualizing the functional demand placed on older adults by everyday living tasks. *Universal Access in the Information Society, 6*, 137–144.

McFadyen, B. J., & Winter, D. A. (1988). An integrated biomechanical analysis of normal stair ascent and descent. *Journal of Biomechanics, 21*, 733–744.

Mourey, F., Pozzo, T., Rouhier-Marcer, I., & Didier, J. P. (1998). A kinematic comparison between elderly and young subjects standing up from and sitting down in a chair. *Age and Ageing, 27*, 137–146.

Prince, F., Corriveau, H., Herbert, R., & Winter, D. A. (1997). Gait in elderly. *Gait and Posture, 5*, 128–135.

Protopapadaki, A., Drechsler, W. I., Cramp, M. C., Coutts, F. J., & Scott, O. M. (2007). Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals. *Clinical Biomechanics, 22*, 203–210.

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V., & Maganaris, C. N. (2006). The biomechanical demands of stair descent in elderly and young adults. *Journal of Biomechanics, 39*, s87.

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V., & Maganaris, C. N. (2008). The demands of stair descent relative to maximum capacities in elderly and young adults. *Journal of Electromyography and Kinesiology, 18*, 218–227.

Reeves, N. D., Spanjaard, M., Mohagheghi, A. A., Baltzopoulos, V., & Magnaris, C. N. (2009). Older adults employ alternative strategies to operate within their maximum capabilities when ascending stairs. *Journal of Electromyography and Kinesiology, 19*, e57–e68.

Rodosky, M. W., Andriacchi, T. P., & Andersson, G. B. J. (1989). The influence of chair height on lower-limb mechanics during rising. *Journal of Orthopaedic Research, 7*, 266–271.

Rowe, P. J., Samuel, D., & Hood, V. (2005). The functional demand placed on the knee flexors and extensors of older adults when undertaking activities of daily living. *Gait and Posture, 22*, s16–s17.

Samuel, D., & Rowe, P. (2009). The effect of ageing on isometric strength through joint range at knee and hip joints in three age groups of older adults. *Gerontology, 55*, 621–629.

Samuel, D., Rowe, P., Hood, V., & Nicol, A. (2011). The biomechanical functional demand placed on knee and hip muscles of older adults during stair ascent and descent. *Gait and Posture, 34*, 239–244.

Schenkman, M., Berger, R. A., Riley, P. O., Mann, R. W., & Hodge, W. A. (1990). Whole-body movements during rising to standing from sitting. *Physical Therapy, 70*, 638–651.

Schultz, A. B. (1992). Mobility impairment in the elderly: Challenges for biomechanics research. *Journal of Biomechanics, 25*, 519–528.

Startzell, J. K., Owens, D. A., Mulfinger, L. M., & Cavanagh, P. R. (2000). Stair negotiation in older people: A review. *Journal of the American Geriatrics Society, 48*, 567–580.

Vandervoort, A. A., Kramer, J. F., & Wharram, E. R. (1990). Eccentric knee strength of elderly females. *Journal of Gerontology, 45*, 125–128.

Verghese, J., LeValley, A., Hall, C. B., Katz, M. J., Ambrose, A. F., & Lipton, R. B. (2006). Epidemiology of gait disorders in community-residing older adults. *Journal of the American Geriatrics Society, 54*, 255–261.

Verghese, J., Lipton, R. B., Hall, C. B., Kuslansky, G., Katz, M. J., & Buschke, H. (2002). Abnormality of gait as a predictor of non-Alzheimer's dementia. *New England Journal of Medicine, 347*, 1761–1768.