

# Estimations of relative effort during sit-to-stand increase when accounting for variations in maximum voluntary torque with joint angle and angular velocity

Kathleen A. Bieryla <sup>a</sup>, Dennis E. Anderson <sup>b</sup>, Michael L. Madigan <sup>b,c,d,\*</sup>

<sup>a</sup> Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States

<sup>b</sup> Department of Engineering Science and Mechanics (MC 0219), Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States

<sup>c</sup> Virginia Tech-Wake Forest School of Biomedical Engineering and Sciences, Blacksburg, VA 24061, United States

<sup>d</sup> Virginia Tech Center for Gerontology, Blacksburg, VA 24061, United States

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## Abstract

The main purpose of this study was to compare three methods of determining relative effort during sit-to-stand (STS). Fourteen young (mean  $19.6 \pm \text{SD } 1.2$  years old) and 17 older ( $61.7 \pm 5.5$  years old) adults completed six STS trials at three speeds: slow, normal, and fast. Sagittal plane joint torques at the hip, knee, and ankle were calculated through inverse dynamics. Isometric and isokinetic maximum voluntary contractions (MVC) for the hip, knee, and ankle were collected and used for model parameters to predict the participant-specific maximum voluntary joint torque. Three different measures of relative effort were determined by normalizing STS joint torques to three different estimates of maximum voluntary torque. Relative effort at the hip, knee, and ankle were higher when accounting for variations in maximum voluntary torque with joint angle and angular velocity (hip =  $26.3 \pm 13.5\%$ , knee =  $78.4 \pm 32.2\%$ , ankle =  $27.9 \pm 14.1\%$ ) compared to methods which do not account for these variations (hip =  $23.5 \pm 11.7\%$ , knee =  $51.7 \pm 15.0\%$ , ankle =  $20.7 \pm 10.4\%$ ). At higher velocities, the difference in calculating relative effort with respect to isometric MVC or incorporating joint angle and angular velocity became more evident. Estimates of relative effort that account for the variations in maximum voluntary torque with joint angle and angular velocity may provide higher levels of accuracy compared to methods based on measurements of maximal isometric torques.

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## 1. Introduction

The ability to perform activities of daily living (ADLs), such as rising from a chair, transferring in/out of bed, and ascending/descending stairs, is reduced in older adults (Alexander et al., 2001; Grabiner and Enoka, 1995; Schultz

et al., 1992; Startzell et al., 2000). One possible reason for this reduced ability is that older adults perform ADLs at a higher level of relative effort compared to young adults (Hortobagyi et al., 2003). Relative effort has been quantified by expressing joint torques during an activity as a percentage of the maximum voluntary torque (Hortobagyi et al., 2003). Accurate assessments of relative effort, therefore, require accurate methods of determining maximum voluntary torque.

Several studies have considered the maximum torque measured during isometric exertions as maximum voluntary torque, and used this torque in assessments of relative

\* Corresponding author. Address: Department of Engineering Science and Mechanics (MC 0219), Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, United States. Tel.: +1 540 231 1215; fax: +1 540 231 4574.

E-mail address: [mmlm@vt.edu](mailto:mmlm@vt.edu) (M.L. Madigan).

effort (Hortobagyi et al., 2003; Hughes et al., 1996; Kotake et al., 1993). For example, Hughes et al. (1996) and Kotake et al. (1993) measured maximum isometric torque at pre-determined knee angles to determine relative effort during sit-to-stand (STS). Hortobagyi et al. (2003) used a similar approach, but attempted to match joint angles during isometric strength measurements with measured angles during the STS task. Joint torque production varies with both joint angle and angular velocity due to the force-length relation (Sale et al., 1982), the force-velocity relation (Westing and Seger, 1989), and variations in muscle moment arm with joint angle (Smidt, 1973). The use of isometric torques as maximum voluntary torques neglects these known sources of variation in torque production during dynamic tasks such as STS. Without taking into account these variations, calculations of relative effort could be misleading.

Mathematical models of joint torque production that account for variations with joint angle and angular velocity have been developed (Anderson et al., 2007; Chow et al., 1999; King and Yeadon, 2002), and could be used to estimate maximum voluntary torque when assessing relative effort. These models were based on the force-length and force-velocity relations, and specific model parameters were determined by fitting joint torque measurements to the model using a least-squares approach. Anderson et al. (2007) developed a 10 parameter function of maximum voluntary joint torque using experimentally collected isokinetic (concentric and eccentric) and isometric torques. A cosine function was used to model the torque-angle relationship, and angular velocity was included by scaling the cosine function by a modified Hill force-velocity model (Hill, 1938). Attractive features of this model are that only 10 parameters are needed to fully characterize the theoretical maximum joint torque as a function of joint angle and angular velocity (compared to more parameters in other models), and these parameters have some physical interpretation (unlike similar models). In addition, this model has been applied to multiple joints and exertion directions whereas other models have only been demonstrated for knee extensor torque (Chow et al., 1999; King and Yeadon, 2002).

It is not clear if estimates of relative effort will differ when using more complex models of maximum voluntary torque compared to using simple measurements of maximum isometric torque. If differences do exist, it would be beneficial to understand the how these estimates differ. Therefore, the main purpose of this study was to compare three methods of determining relative effort during STS. These methods differ in their definition of maximum voluntary torque, and the instant of maximum exertion during the STS trial. The STS task was chosen because of its reliance on strength and its use as a clinical tool of functional capability. It was hypothesized that accounting for variations in maximum voluntary torque with joint angle and angular velocity will increase the estimated relative effort during STS compared to not accounting for these variations.

## 2. Methods

Fourteen young (7M 7F, mean age of  $19.6 \pm \text{SD } 1.2$  years old; mean mass of  $67.9 \pm 8.7$  kg; mean height of  $168.6 \pm 8.5$  cm) and 17 older (9M 8F, mean age of  $61.7 \pm 5.5$  years old; mean mass of  $67.9 \pm 8.7$  kg; mean height of  $168.6 \pm 8.5$  cm) adults were recruited from the university population and surrounding community to participate in the study. Criteria for inclusion in the study were lack of injury or illness that could confound results or endanger the participant, and a moderate level of regular physical activity (exercised 2–4 days/week). In addition, a medical screening was performed on older participants by a physician to exclude individuals with cardiac, musculoskeletal, neurological, otological, or respiratory disorders. The study was approved by the Virginia Polytechnic Institute and State University Institutional Review Board, and written consent was obtained from all participants prior to participation.

The experimental protocol consisted of two parts. During the first part, six STS trials were completed. The participant sat on an armless, backless chair of adjustable height. The height of the chair was adjusted so the participant's thighs were parallel to the floor. Feet were spaced shoulder-width apart and adjusted anteriorly and posteriorly so that the ankle was dorsiflexed  $20^\circ$  from the anatomical position. The upper extremities were folded across the chest throughout all trials. Two STS trials were performed at each of three self-selected speeds. Three different sets of directions were given to the participants for the three speeds. For normal speed trials, the instructions were to "rise from the chair"; for slow speed trials, the instructions were to "stand as slowly as possible"; and for fast speed trials, the instructions were to "stand as fast as you can". Although these speeds were self-selected, the peak angular velocities at the hip, knee, and ankle were significantly different from each other ( $p < 0.001$ ). No significant left-right asymmetries were observed during any trials.

During the second part of the experimental protocol, lower extremity strength measurements were performed to determine the parameters of the mathematical model of maximum voluntary torque for each participant. The protocol for these measurements has been explained in detail elsewhere (Anderson et al., 2007) and thus will only be summarized here. A regimen of isokinetic (concentric and eccentric) and isometric maximum voluntary contractions (MVCs) for hip extension, hip flexion, knee extension, knee flexion, ankle plantar flexion, and ankle dorsiflexion were collected on the right leg using a Biodex System 3 dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA). The protocol was similar for each joint/direction combination. A passive torque profile was first recorded by moving the dynamometer slowly ( $5 \text{ deg/s}$ ) through the entire participant-specific range of motion while the participant was relaxed. Two isometric MVCs were recorded at each of six joint angles spaced evenly throughout the range of motion. Four isokinetic concentric

MVCs were recorded at each of two velocities (60 and 120 deg/s for the ankle and hip, and 75 and 150 deg/s for the knee). Four high speed concentric MVCs were also recorded. In these tests, the maximum isokinetic velocity of the Biodex (500 deg/s) was used, and the participant was encouraged to move as quickly as possible. This velocity was faster than any participant could achieve, and doing so effectively minimized resistance for these contractions. Four isokinetic eccentric MVCs were performed at a single velocity (60 deg/s for the ankle and hip, and 75 deg/s for the knee). Five minute rest periods were included throughout the protocol to help prevent neuromuscular fatigue.

During the STS trials, whole-body kinematics and ground reaction forces were recorded. Twenty-six reflective markers were placed bilaterally over selected anatomical landmarks on the head, arms, trunk, and lower extremities. Marker positions were sampled at 100 Hz using a Vicon 460 motion analysis system (Vicon, Lake Forest, CA, USA) and low-pass filtered at 7 Hz (second order zero-phase-shift Butterworth filter) (Winter, 2005). Separate force platforms were positioned under the chair (Bertec Corporation, Columbus, OH, USA) and under the right foot (AMTI, Watertown, MA, USA). Ground reaction forces were sampled at 1000 Hz and low-pass filtered at 7 Hz (fourth order zero-phase-shift Butterworth filter). During the strength testing, joint angle, angular velocity, and torque were collected using a Biodex System 3 dynamometer, sampled at 200 Hz using LabVIEW 7.1 (National Instruments Corporation, Austin, TX, USA) and low-pass filtered at 5 Hz (fourth order zero-phase-shift Butterworth filter). The gravitational torque was estimated (in concert with the passive joint torques) by a least squares fit of the passive torque profile and subtracted from torque measurements.

Sagittal plane joint torques in the right lower extremity during each STS trial were estimated using an inverse dynamics analysis. The body was modeled as a two-dimensional system of four rigid links, connected by frictionless pin joints, that included the right foot, shank, thigh, and a single head/arms/trunk (HAT) segment. Link masses (Pavol et al., 2002) and inertial characteristics (de Leva, 1996) were defined using existing anthropometric models. Joint torques were estimated from seat-off to standing for the right ankle, knee, and hip using the governing Newton–Euler equations as described by Winter (2005). Seat-off was defined as the instant the participant lost contact with the seat as determined from the force platform under the chair. The end of the trial was defined as the instant when the vertical motion of the right shoulder marker ceased (Lomaglio and Eng, 2005). The parameters of the mathematical model of maximum voluntary torque were determined for each participant using the experimentally-collected strength measurements and a simulated annealing algorithm (Anderson et al., 2007). This model provided the ability to predict the participant-specific theoretical maximum voluntary torque based

on measurements of instantaneous joint angle and angular velocity during STS trials.

Three methods of determining relative effort from joint torques were investigated (Fig. 1). Method 1 (M1) first determined the peak joint torque during STS, then normalized this torque by dividing it by the non-angle-specific maximum isometric torque recorded from the Biodex (Hughes et al., 1996; Kotake et al., 1993). Method 2 (M2) first determined the peak joint torque during STS, then normalized this torque by dividing it by the theoretical maximum joint torque predicted by the model using the instantaneous values of joint angle and angular velocity (Anderson et al., 2007). Method 3 (M3) first normalized joint torques throughout STS by dividing each instantaneous value by the theoretical maximum voluntary torque, then determined peak relative effort as the peak value of this normalized torque.

The effects of method, speed, and their interaction on relative effort during STS were investigated using a two-way repeated-measures ANOVA. Preliminary analysis indicated no effect of age, so it was not included in the analysis. Extension torques dominated throughout the STS trials with only sporadic flexion torques in a small percentage of trials. Therefore, our analysis was limited to relative effort of extension torques. Pair-wise comparisons following significant main effects or interactions were evaluated using paired *t*-tests and Holm's sequential Bonferroni procedure to control for family-wise error rate (Green and Sal-kind, 2003). In a secondary analysis, the difference in relative effort between M3 and M1 was calculated for each subject and a one-way ANOVA on speed was conducted. Four individual relative effort values (three knee extension, one ankle plantar flexion) were considered extreme outliers (greater than mean plus seven standard deviations), and removed prior to statistical analysis. All statistical analysis was completed in JMP 5.1.2 (Cary, NC) with  $p \leq 0.05$  indicating statistical significance.

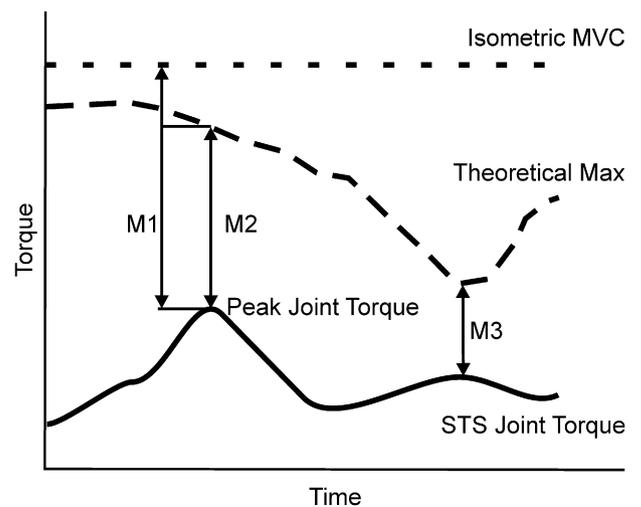


Fig. 1. Sample STS data to illustrate the three methods of calculating relative effort.

3. Results

Relative hip extension effort showed main effects of speed ( $p = 0.002$ ), method ( $p < 0.001$ ), and a speed  $\times$  method interaction ( $p < 0.001$ ) (Fig. 2). Pair-wise comparisons between speeds revealed the relative effort used to complete STS at a slow speed ( $24.5\% \pm 13.6\%$ ) was higher than at a normal speed ( $21.0\% \pm 10.4\%$ ). Pair-wise comparisons between methods revealed the relative effort calculated using M3 ( $26.3\% \pm 13.5\%$ ) was higher than M1 ( $23.5\% \pm 11.7\%$ ), and both were higher than M2 ( $18.3\% \pm 12.0\%$ ). Pair-wise comparisons to evaluate the speed  $\times$  method interaction revealed relative effort at a normal

speed was higher for M3 ( $25.2\% \pm 11.1\%$ ) than M1 ( $20.0\% \pm 8.6\%$ ) and M2 ( $17.8\% \pm 10.1\%$ ). Relative effort at a fast speed was higher for M3 ( $27.4\% \pm 17.0\%$ ) than M1 ( $21.3\% \pm 10.5\%$ ) and M2 ( $19.2\% \pm 12.5\%$ ). Lastly, relative effort at a slow speed was higher for M1 ( $29.3\% \pm 13.4\%$ ) and M3 ( $26.2\% \pm 11.8\%$ ) than M2 ( $18.1\% \pm 13.4\%$ ).

Relative knee extension effort showed main effects of speed ( $p < 0.001$ ), method ( $p < 0.001$ ), and a speed  $\times$  method interaction ( $p < 0.001$ ) (Fig. 2). Pair-wise comparisons between speeds revealed the relative effort at a fast speed ( $87.0\% \pm 30.3\%$ ) was higher than at a normal speed ( $70.4\% \pm 22.6\%$ ), and both were higher than at a slow speed ( $47.4\% \pm 13.9\%$ ). Pair-wise comparisons between methods revealed the relative effort calculated using M3 ( $78.4\% \pm 32.2\%$ ) was higher than M2 ( $75.0\% \pm 27.2\%$ ), and both were higher than M1 ( $51.7\% \pm 15.0\%$ ). Pair-wise comparisons to evaluate the speed  $\times$  method interaction revealed relative effort at a normal speed was higher for M3 ( $80.7\% \pm 23.4\%$ ) and M2 ( $77.5\% \pm 20.3\%$ ) than M1 ( $53.2\% \pm 11.7\%$ ). Relative effort at a fast speed was higher for M3 ( $102.5 \pm 33.0\%$ ) than M2 ( $96.1\% \pm 24.6\%$ ) and both were higher than M1 ( $62.8\% \pm 12.8\%$ ). Additionally M2 was higher than M1. Lastly, relative effort at a slow speed was higher for M3 ( $53.2\% \pm 11.7\%$ ) and M2 ( $51.4\% \pm 14.1\%$ ) than M1 ( $38.9\% \pm 9.1\%$ ).

Relative ankle plantar flexion effort showed main effects of speed ( $p < 0.001$ ) and method ( $p < 0.001$ ) (Fig. 2). Pair-wise comparisons between speeds revealed the relative effort at a slow speed ( $29.1\% \pm 14.2\%$ ) was higher than at a normal speed ( $24.5\% \pm 12.0\%$ ), and both were higher than at a fast speed ( $21.2\% \pm 10.7\%$ ). Pair-wise comparisons between methods revealed the relative effort calculated using M3 ( $27.9\% \pm 14.1\%$ ) and M2 ( $26.1\% \pm 12.4\%$ ) were higher than M1 ( $20.7\% \pm 10.4\%$ ).

Speed had a significant effect on the M3-M1 difference for relative hip extension effort ( $p < 0.001$ ) and relative knee extension effort ( $p < 0.001$ ) (Fig. 3). Post-hoc Student's  $t$ -test revealed M3 – M1 for relative hip extension effort was higher at a fast speed ( $5.6\% \pm 13.0\%$ ) and at a

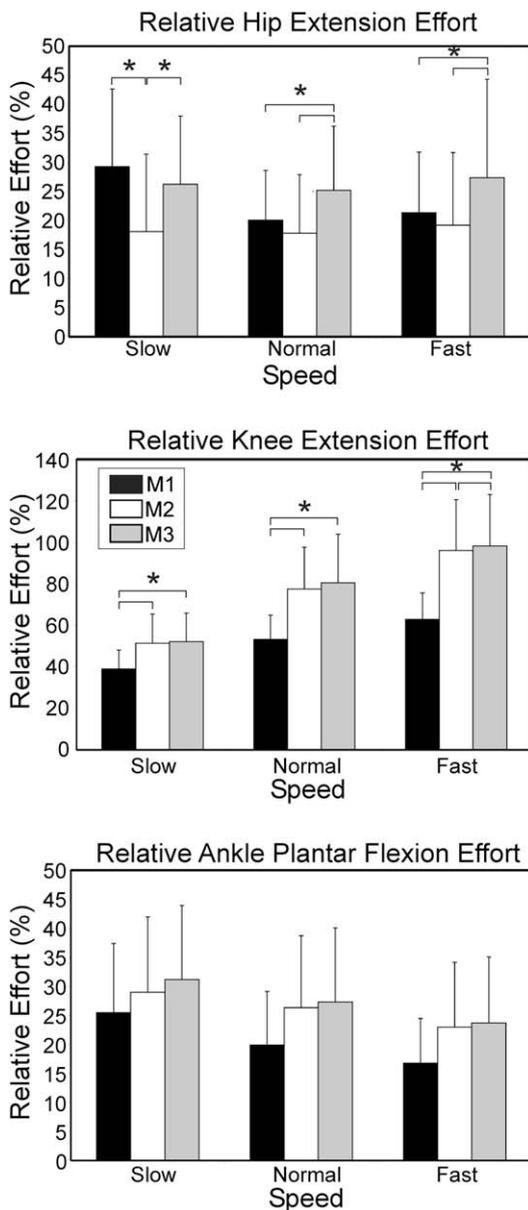


Fig. 2. Peak relative effort for hip extension, knee extension, and ankle plantar flexion of all participants during STS for all three speeds and all three methods. Error bars represent standard deviation. \* indicates significance  $p < 0.05$ .

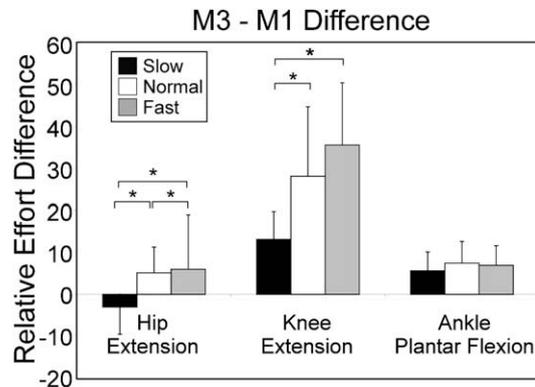


Fig. 3. Difference in M3 – M1 for hip extension, knee extension, and ankle plantar flexion for the three speeds. Error bars represent standard deviation. \* indicates significance  $p < 0.05$ .

normal speed ( $5.1\% \pm 6.0\%$ ) than at a slow speed ( $-3.0\% \pm 6.5\%$ ). The difference M3 – M1 for relative knee extension effort was higher at a fast speed ( $35.5\% \pm 14.8\%$ ) than at a normal speed ( $28.1\% \pm 16.6\%$ ), and both were higher than at a slow speed ( $13.1\% \pm 6.6\%$ ).

#### 4. Discussion

The main purpose of this study was to compare three methods of determining relative effort during STS. The three methods provided different assessments of relative effort. Methods that incorporated variations in maximum voluntary torque with joint angle and angular velocity yielded higher relative efforts than methods based on isometric MVC torques. Additionally, it was shown that peak joint torques do not necessarily coincide temporally with maximum relative effort. Although no “gold standard” exists to determine which of these methods is most accurate, it seems reasonable that employing a method which incorporates variations in joint torque production with joint angle and angular velocity, and which does not limit the analysis to peak joint torques, would lead to more accurate assessments of relative effort.

Several limitations of this study exist. First, inertial effects and misalignment of the joint axis may introduce errors in dynamometer data during strength testing (Herzog, 1988). To minimize these effects, we used only isokinetic/isometric torque data, and exercised care in joint alignment on the dynamometer. In addition, actual joint angle and angular velocity may differ from dynamometer recordings (King and Yeadon, 2002). Second, it was assumed that all participants provided maximum effort during strength testing in response to verbal encouragement. Sub-maximal exertions could result in a model that underestimates the theoretical maximum voluntary joint torque, and therefore overestimate relative effort. Third, the calculation of joint torques during STS, as in all inverse dynamics analyses, was susceptible to errors due to skin movement artifacts, marker placement, and assumptions in determining segment mass and inertial characteristics. Fourth, the model used to represent the theoretical maximum voluntary torque has limitations (Anderson et al., 2007). In particular, the model used a least squares approach to fit the model to the experimental data and obtain the model parameters. With this approach, predicted torque values from the model could be less than actual strength measurements. This may account for some relative knee extension effort values exceeding 100%. Finally, because method  $\times$  speed interactions were present, the results between the three methods may vary if other activities are studied.

In general, accounting for variations in joint torque production with joint angle and angular velocity led to higher levels of relative effort compared to methods which do not account for these variations. Peak relative effort during STS at a normal speed using M3 ( $80.6\% \pm 23.4\%$ ) was greater than M2 ( $77.5\% \pm 20.3\%$ ) and M1 ( $53.2\% \pm 11.8\%$ ). Additionally, M3 was generally greater than rela-

tive effort values reported in prior studies. Mean relative knee extension effort for healthy young adults during STS at a normal speed was 30% (Kotake et al., 1993), 34% (Hughes et al., 1996), and 42% (Hortobagyi et al., 2003) and for healthy older adults 80% (Hortobagyi et al., 2003). It is important to note that age was not a significant factor, which is inconsistent with other studies (Hortobagyi et al., 2003), and, therefore, could confound these comparisons. It is possible that the lower average age of the older adults compared to past studies may account for the lack of a significant difference between age groups. Additionally the difference between M3 and M1 was significantly higher in the fast STS trials than in the slow trials for both hip extension and knee extension. This may be due to the fact that as movement velocity increases, the maximum voluntary torque decreases due to the nature of the force-velocity relationship. These results suggest that the benefit of including angular velocity in a model when calculating relative efforts during a dynamic task increases as task velocity increases.

Differences between M2 and M3 indicated that the instant of peak relative effort did not necessarily coincide temporally with the instant of peak joint torque. Past calculations of relative effort during STS made the implicit assumption that the timing of peak relative effort coincided with the peak joint torque (Hughes et al., 1996; Kotake et al., 1993). This was not the case for hip extension, as the relative effort calculated by M2 ( $18.3\% \pm 12.0\%$ ) was significantly lower than M3 ( $26.2\% \pm 13.5\%$ ). In fact, the instant of peak relative effort differed by more than 0.1 s (or approximately 20% of STS duration) from the instant of peak joint torque at the hip in 50.0% of trials, at the knee in 11.0% of trials, and at the ankle in 24.2% of trials. This is due to variations in joint angle and angular velocity decreasing the theoretical maximum joint torque from the isometric value (Fig. 1). In an attempt to account for variations in joint torque with joint angle, studies have identified the joint angle at which peak torques occur during a task of interest, and use this same angle during maximum voluntary torque measurements (Hortobagyi et al., 2003). Based on the differences between M2 and M3 found in the present study, the peak torques identified with this approach may not correspond to peak relative effort, and as a result, may lead to erroneous estimates of relative effort. These results emphasize the importance of taking into account the dynamic nature of the task when evaluating relative effort via joint torques.

#### 5. Conclusions

In conclusion, incorporating variations in maximum voluntary torque with joint angle and angular velocity was shown to have an effect on relative effort during STS, especially for tasks with higher velocities. It was also suggested that these estimates of relative effort may provide higher levels of accuracy compared to methods based on measurements of maximal isometric torques. Although

the focus of this study was STS, these conclusions likely apply to other tasks during which relative effort may be important, and could lead to more accurate assessments of relative effort in older adults during ADLs.

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**Kathleen A. Bieryla** earned her M.S. in Mechanical Engineering in the Kevin P. Granata Musculoskeletal Biomechanics Laboratory at Virginia Tech, and is currently pursuing a Ph.D. Her current research focuses on falls in the older adults with specific interests in motor learning.



**Dennis E. Anderson** earned his M.S. in Engineering Mechanics at Virginia Tech, and is currently in the Kevin P. Granata Musculoskeletal Biomechanics Laboratory at Virginia Tech pursuing a Ph.D. His research focuses on musculoskeletal modeling with specific interest in muscular and skeletal loading during human movement.



**Michael L. Madigan** earned a PhD degree in Biomedical Engineering from Virginia Commonwealth University in 2001. He is currently an Associate Professor in the Department of Engineering Science and Mechanics at Virginia Tech, and Director of the Kevin P. Granata Musculoskeletal Biomechanics Laboratory. His research focuses on the dynamics and control of human movement, with specific interest in balance, aging, and neuromuscular fatigue.