Short Communication

Characterizing Asymmetry across the Whole Sit to Stand Movement in Healthy Participants

Jonathon Schofield [(a)]
Dr. Eric Parent [(b)]
Justin Lewicke[(c)]
Dr. Jason Carey[(d)]
Dr. Marwan El-Rich [(e)]
Dr. Samer Adeeb [(f)]

(a) Dept. of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, T6G 2R3, Ph: 1(780) 399 8738, email: jsschofi@ualberta.ca

(b) Dept. of Physical Therapy, University of Alberta, Edmonton, Canada, T6G 2R3, Ph: 1(780) 492 8889, email: eparent@ualberta.ca

(c)Syncrude Center, Glenrose Rehabilitation Hospital, Alberta Health Services, 10230 111 Ave Edmonton, Canada, T5G 0B7, email: Justin.Lewicke@albertahealthservices.ca

(d) Dept. of Mechanical Engineering, University of Alberta, Edmonton, Alberta, T6G 2R3, Ph: 1(780) 492 7168, email: jpcarey@ualberta.ca

(e) Dept. of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, T6G 2R3, Ph: 1(780) 492 6678, email: elrich@ualberta.ca

(f) Dept. of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, T6G 2R3, Ph: 1(780) 492 2190, email: adeeb@ualberta.ca

Keywords: Sit-to-Stand, Symmetry, Whole Cycle, Biomechanics, Motion Capture

Word Count: 2180 (excluding citations and references)

Abstract

Sit-to-stand transfer (STS) is a common yet critical prerequisite for many daily tasks. Literature conducted on healthy STS often assume the body to behave symmetrically across the left and right side; yet only a few studies have been conducted to investigate this supposition. These studies have focused on a single numerical indicator such as peak joint moment (JM) values to describe symmetricity; however, STS is a dynamic and time dependent movement. This study addresses the validity of peak value analyses through the introduction of a time based peak-offset measure and proposes two time-dependent techniques to further characterize asymmetry and assesses their feasibility in ten (10) healthy male participants. JM and joint power (JP) over the whole STS movement was determined using motion capture and inverse dynamics. Using a paired one-tailed t-test differences were found in the time at which the left and right side reached peak values in all lower extremity joints with exception of the hip JM ($p<0.05$). Using a measure of JM and JP straight-difference it was determined that the ankle joint displayed the largest number of JM and JP development strategies of all the lower extremity joints. Finally, through numerical integration of the JM and JP data with respect to time, it was found that the longer one side spends dominating the movement, the larger the excess angular impulse and work that can be expected from that side. The results suggest that when analyzing STS movements, one must be aware of the potential asymmetry present even in healthy movements. Furthermore, a simple peak JM or JP analysis may not fully describe the extent of these asymmetries.

Introduction

Sit-to-stand (STS) movements are a functional prerequisite for many daily tasks and consequently an independent lifestyle (Burnett *et al.*, 2011; Fotoohabadi *et al.*, 2012). Therefore, understanding the biomechanics to accomplish STS is necessary for rehabilitation and therapeutic programs focused on patients with lower extremity impairment.

Clinically, STS symmetry can be used as an assessment tool for lower extremity function. STS symmetry has been used to evaluate knee function following arthroplasty focusing on peak vertical ground reaction forces (VGRF) (Boonstra *et al.*, 2008, 2010; Christiansen *et al.*, 2011) as well as assess movements in the elderly, hemiparetic and amputee populations among others (Agrawal *et al.*, 2011; Fotoohabadi *et al.*, 2012; Gao et al., 2011; O'Meara & Smith, 2005; Roy *et al.*, 2007). Although asymmetry is an indication of impairment, perfect symmetry is not necessarily exhibited in healthy populations (Lundin et al., 1995).

When quantifying healthy STS movements, several studies assume bilateral symmetry, where joint moments (JMs) are assumed contralaterally equivalent across the left and right sides (Kuo et al., 2009; Roberts & McCollum, 1996; Sibella et al., 2003; Yoshioka et al., 2009). Yet, lower limb kinetic asymmetry has been widely demonstrated in healthy populations performing tasks such as gait (Seeley *et al*., 2008, 2010), or during the propulsive phase of gait in elderly subjects (Sadeghi *et al.*, 2004). Furthermore, strength asymmetry has been demonstrated in healthy populations; exhibiting stronger quadriceps and weaker hamstrings in their dominant sides during knee flexion and extension (Lanshammar & Ribom, 2011).

Limited research has been conducted on healthy STS symmetry. Asymmetry was shown in the sagittal JMs of the hips in elderly (n=7, mean [SD] age: 22.9 [1.0]) and young (n=7, mean [SD] age: 74.3 [4.1]) participants with further asymmetry at the knees of the young group (Lundin et al., 1995). Burnett *et al*. evaluated peak VGRFs in relation to leg dominance and found no significant difference between sides (Burnett et al., 2011). However, these two studies were limited to the evaluation of peak JMs and VGRFs, respectively, focusing on a single point in the STS movement to evaluate symmetry.

To address this limitation, while studying a single above knee amputee, Gao *et al.* assessed STS asymmetry using principle-component-analysis. This technique accounted for whole cycle movements in all three body planes; a unique approach for STS based research. However, able bodied research rarely addresses movements across the whole STS cycle (Gao et al., 2011). It is important to recognize STS is a dynamic movement in which biomechanical requirements follow a time dependent cycle. Peak values are achieved at a single instant during that cycle and thus may not be a comprehensive measure of asymmetry.

This study addresses the validity of peak value analyses through the introduction of a time based, peak-offset measure. Furthermore two novel methods for evaluating STS symmetry, while incorporating whole cycle data are proposed and their feasibility analyzed.

Methods

Ten healthy male participants were recruited internally through the institution's engineering faculty (Table 1). Males were selected to remove possible biomechanical gender differences present in non-STS related motion analysis (Moisio *et al*., 2003). Potential participants reporting prior or current conditioning and/or injuries that may affect their STS movements were excluded from the study. Ethics approval was obtained through the institution's ethics board and informed consent was obtained prior to participation.

Insert Table 1

Reflective markers (1.5 cm diameter) were positioned on participants according to the Helen Hayes protocol (Kadaba *et al*., 1990). Additional markers were adhered between the clavicles, centered on the sternum and affixed to the C7, to capture torso position. An 8 camera, Eagle Digital motion capture system (Motion Analysis Corp., Santa Rosa, CA, USA), sampling at 120Hz, and two force plates (Advanced Mechanical Technology Inc., Newton, MA, USA), sampling at 2400Hz captured marker motions and GRFs, respectively.

A backless, armless, 48cm tall chair was positioned such that participants could place one foot approximately centered on each force place (Lundin *et al*., 1995). Participants were instructed to sit comfortably toward the front of the chair, and symmetricity of the initial posture was visually verified prior to each trial. To remove inertial effects of upper limb movements, subjects folded their arms across their chest. When prompted, participants rose at a self-selected pace. The procedure included 10 trials for each participant.

Marker motion data was smoothed using a 4Hz, fourth-order, Butterworth filter, and imported into Visual 3D software (C-Motion Inc., Germantown, MD, USA) for inverse dynamic calculations. Each participant's body-segment properties were input according to height and mass dependant 50th percentile anthropometric data (Winter, 1990; Zatsiorsky, 2002). Lower extremity JMs, joint angles and joint angular velocities were extracted for this analysis. JM values were normalized to participant body mass and height. Joint power (JP) was determined through the multiplication of the normalized JM and joint angular velocity data.

To determine total JMs and JPs, the Euclidian Norm was used by treating orthogonal JMs about each joint using Eq. (1). This procedure was repeated for JP data.

Insert Equation 1

STS was defined as occurring during the time interval between mass transfer (torso anterior rotation characterized by hip flexion) and the point at which joint motion ceased (Miyoshi, *et al*., 2005). Initiation time was determined when the hip joint angle fell outside +/- 3 standard deviations of the initial static position (based on averaging the first 20 data points); completion was determined when the hip joint angle fell within +/- 3 standard deviations of the final static position (based on averaging the final 10 data points). Cycle time was normalized to a pseudo time scale of % STS completion. JM and JP curves were averaged for each participant's 10 trials on the left and right side independently.

<u>Peak Offset</u>

The peak JM (or JP) value was defined as the maximum absolute value occurring during the STS cycle. The times, in units of % STS completion, at which peak values occurred on the left and right side for each joint were collected independently (Fig. 1). The time at which each joint's peak value occurred was arranged into two groups, first side to peak and last side to peak. A paired, one-tailed t-test was conducted to test for a significant difference in the means of these groups ($P<0.05$).

Insert Figure 1

Straight-Difference

To characterize side dominance, straight difference (SDIF) plots were created by subtracting the averaged right side JM (JP) data from the averaged left for each joint of each participant. Positive (negative) SDIFs value indicated left (right) side dominance (Fig. 1).

SDIF plots were categorized according to the number of slope reversals present. A slope reversal was defined as a shift in a plot's slope from positive to negative (or negative to positive) with amplitude in excess of 25% the absolute global maximum of the plot. Therefore, this procedure neglects minor fluctuations in the SDIF data. Corresponding to each joint, participants were categorized based on the number of slope reversals present.

Angular Impulse, Work and Time

Percent angular impulse (PAI) and percent work (PW) enabled characterization of the relationship between length of time a side dominated JM (or JP) development, and excess impulse (or work) that resulted from that side. Positive PAI (PW) was derived through exclusive summation of the positive regions of the SDIF JM (JP) plot multiplied by the 2% time interval between each JM (JP) data point. This numerical integration was then repeated for the negative components. Therefore, the positive (negative) integral component represents the total excess PAI or PW contributed from the left (right) side (Fig. 2). The percentage of the cycle a JM (JP) SDIF plot remained positive (negative) was recorded and defined as the positive %time (negative %time) (Fig. 2).

Insert Figure 2

Results

Peak Offset

Peak offset values ranged from 0% through 40% completion of STS. On average the ankle produced the largest JM and JP offset values of the three joints (3.6% ±5.15% time and 12.0% ±14.3% time respectively). The knee had the smallest average peak offset for both JM and JP values (0.80% ±1.03% time and 1.00% ±1.05% time respectively). Significant difference was found in the peak times of both JM and JP values of all joint with exception of hip JM values ($P<0.05$) (Table 2).

Insert Table 2

Straight-Difference

Figure 3 plots the slope reversal of each participant according to joint. Table 3 highlights the number of slope reversals demonstrated by each participant and groups based on the number of reversals demonstrated. The ankle demonstrated the most slope reversal groups of all the three joints; participants demonstrated 0, 1, 2 or 3 JM, and 2, 3, 4, 5 or 6 JP slope reversals. As a result participant ankles can be divided into 4 JM and 5 JP groups. JM data at the knee and hip both show 3 groupings representative of 1, 2 or 3 and 1, 2 or 4 reversals respectively. JP at the knee and hip can be divided into 3 groups and 4 groups, respectively.

Insert Figure 3

Insert Table 3

Angular Impulse, Work and Time

Fig. 5 plots for the length of time a side dominates and the excess PAI and PW contributed from that side. In total, the participant group produced 10 positive PAI (PW) values and 10 corresponding positive %time values at each joint (similarly 10 negative PAI (PW) and %time values). It is evident that the longer a side spent dominating the STS cycle, the greater the excess PAI (or PW) contribution from that side. This relationship is presented in all but the left hip and knee PW data where the largest excess PW contributions occur when the left side dominates approximately 45 to 75% of the STS cycle.

Insert Figure 4

Discussion

The literature typically addresses healthy STS asymmetry through a single numerical indicator, such as peak JMs or GRFs (Burnett, *et al.*, 2011; Boonstra, *et al.*, 2010; Christistiansen, *et al.*, 2011; Argawal, *et al.*, 2011; Lundin, *et al.*, 1995). Although peak values quantify the maximum requirements of the task, they neglect how and when the body arrives at this condition.

Significant peak offsets were found in the ankle and knee JM and for all three joints for JP ($p<0.05$). Therefore, comparing peak values may only evaluate maximum conditions and does not necessarily compare values from the same point in time. Consequently peak analyses may not sufficiently characterize asymmetry as a whole. The ankle produced the largest average JM and JP peak offset of all joints, suggesting that ankle symmetry should be evaluated using a time dependent measure. However, smaller peak offset values were found at the knee. Therefore, determining clinically relevant offset values would enable further understanding of the validity a peak analysis holds at each joint.

The proposed straight-difference method enables characterization of STS strategies based on slope reversals. These reversals are an indication of asymmetry in the rate of JM (or JP) development across the body. Either one joint is reducing, or the contralateral side is increasing, its excess contribution. Therefore the different numbers of reversals during a STS movement illustrates different strategies for which the body shares JM (or JP) requirements between sides. The ankle was determined to have the largest number of strategies, for both JM and JP (4 and 5 respectively) which is believed to result from the high mobility of the joint and its role in balance and stability (Hylton, *et al*., 2005; Hoch, *et al*., 2005). No apparent relationship was present between participants across joints. For instance participants 1 and 5 both demonstrated a 3 reversal ankle JM strategy. Yet at the knee and hip participant 1 showed 2 and 4 reversals respectively where participant 5 demonstrated 3 and 2 reversals respectively. The lack of commonality suggests that reversal strategies of one joint may not be predictable by viewing the other two. As seen in Figure 3, a vast array of STS strategies were present in the able bodied group. These numerous strategies to perform a relatively simple movement further reiterate the complexity of predicting asymmetry during this task. Several variables beyond those examined in this study may affect asymmetry such as individual inequalities in limb proportions, small variations in foot placement and strength dominance among others.

The PAI, PW and time plots illustrated an intuitive relationship: the amount of excess angular impulse (work) of one side increased with the time that side spent dominating JM (JP) development (excluding left-dominant knee and hip PW data). This suggests that the time a side dominates may be a more appropriate measure of asymmetry than a simple peak analysis. It is possible one side will achieve a higher peak than the other, yet spend minimal time dominating. By employing a peak analysis dominance of the movement would be mislabelled. These PAI, PW and time measures have the potential to robustly label side dominance as they account for asymmetry over the duration of the STS movement. However, further investigation with a larger sample size is warranted to explicitly quantify the nature of these relationships.

Limitations of this study lie in the instructed posture of the participants and the sample size. Participant rose from a standard chair height with arms folded across their chest. By no means do these variables account for every configuration present in day-to-day movements, and consequently may affect the symmetry of STS movements. Furthermore a sample size of 10 was used to evaluate the feasibility of the proposed symmetry measures. Collected data often presented relatively high standard deviations. Although this may weaken statistical power, it further reiterates the variation in symmetry of healthy populations; this is especially evident in Figure 3. Asymmetry in STS presents itself unpredictably and is not necessarily captured through peak values alone.

In conclusion, the able-bodied sample group (n=10) demonstrated an array of STS strategies. Peak JM and JP values were found to occur at different times during the movement therefore questioning the validity of peak analyses. Two proposed methods, evaluating slope reversals in SDIF plots, and analyzing the relationship between PAI, PW and time, allowed for characterization of asymmetry over the duration of the STS movement; perhaps a more comprehensive measure. Further understanding these asymmetries present in STS may be particularly relevant in studying affected populations. As STS symmetry is being incorporated in measurements of lower extremity function (Agrawal *et al*., 2011; Boonstra *et al*., 2008, 2010; Christiansen *et al*., 2011; Fotoohabadi *et al*., 2012; Gao et al., 2011; O'Meara & Smith, 2005; Roy *et al*., 2007), it is pertinent to understand STS is a time dependant movement an evaluation of peak values alone holds inherent limitations.

Conflict of Interest Statement

The authors have no financial or personal conflicts of interest to declare.

Acknowledgements

Partial funding of this study was provided by Natural Sciences and Engineering Research Council of Canada. This council had no influence on this study or paper.

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Table 1 Participant Summary

Where BMI signifies body mass index, Min and Max represent the minimum and maximum values present in the sample group, and SD the standard deviation among participants.

	Age (yrs)	Height (m)	Mass (Kg)	BMI (kg/m^2)
Min	20	1.90	49	18.22
Max	35	1.64	79	25.56
Mean	25.4	1.77	70.5	22.55
SD	4.2	0.09	8.7	2.44

Equation (1) The Euclidian Norm for Joint Moments

The total resultant moment for each joint was defined as the Euclidian Norm vector summation of the anteroposterior (ap), medial-later (ml) and superior-inferior (si) direction moment components for each leg.

$$JM_{total} = \sqrt{JM_{ap}^2 + JM_{ml}^2 + JM_{si}^2}$$

Figure 1 Graphical Representation JM

Graphical representation knee JM plot and resulting SDIF plot for an individual participant's knee. Where JM and SDIF represent joint moment and straight difference respectively, units are given in Newton meters per kilogram (Nm/Kg) normalized to body mass (BM) and body height (BH)

(a) Procedure to identify the time at which each side's peak occurred with peak offset corresponding to the interval between the left and right side %STS Completion values. This procedure was conducted for both JM and JP curves at each joint for each participant.

(b) Procedure to identify SDIF (left JM – Right JM) from the JM data. This procedure was conducted for both JM and JP curves at each joint for each participant.

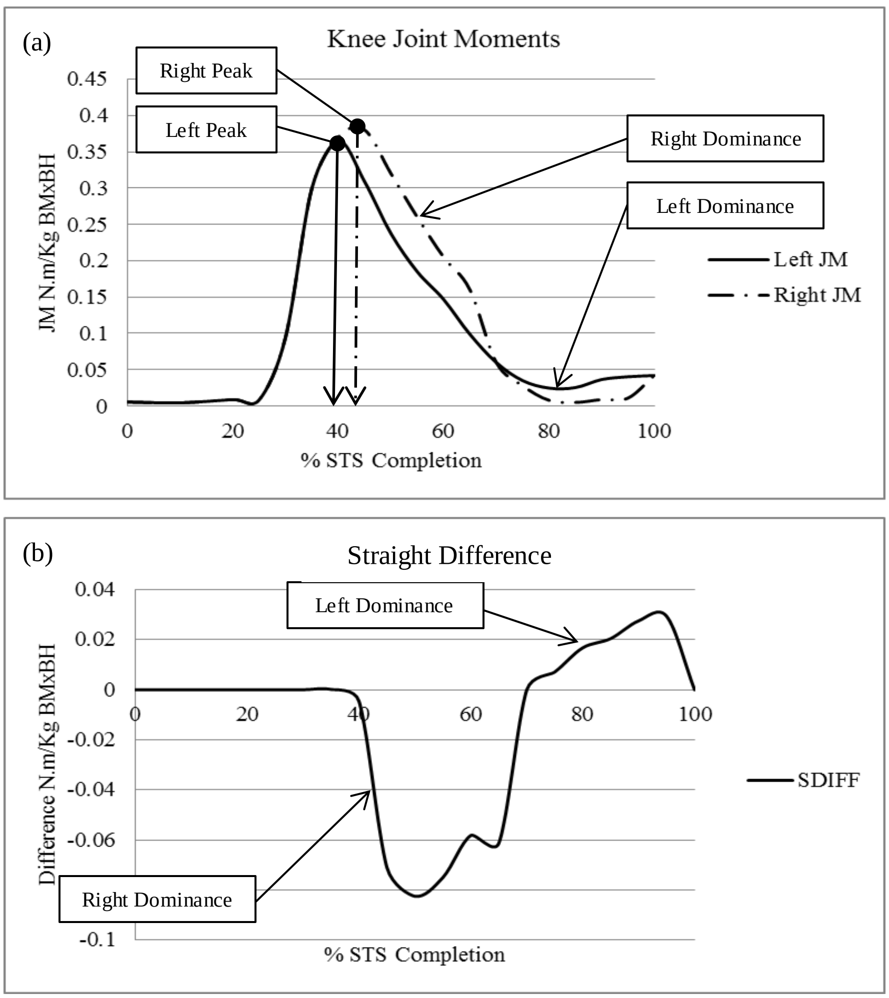

Figure 2 Graphical Representation of Percent Angular Impulse Procedure

Top: identification of areas of excess JM contribution. Bottom: integration of the SDIFF curve to identify the excess PAI values. Negative PAI is representative of right side excess and positive values indicate areas of left side excess. The time period over which these areas of excess occur are highlighted in the figure.

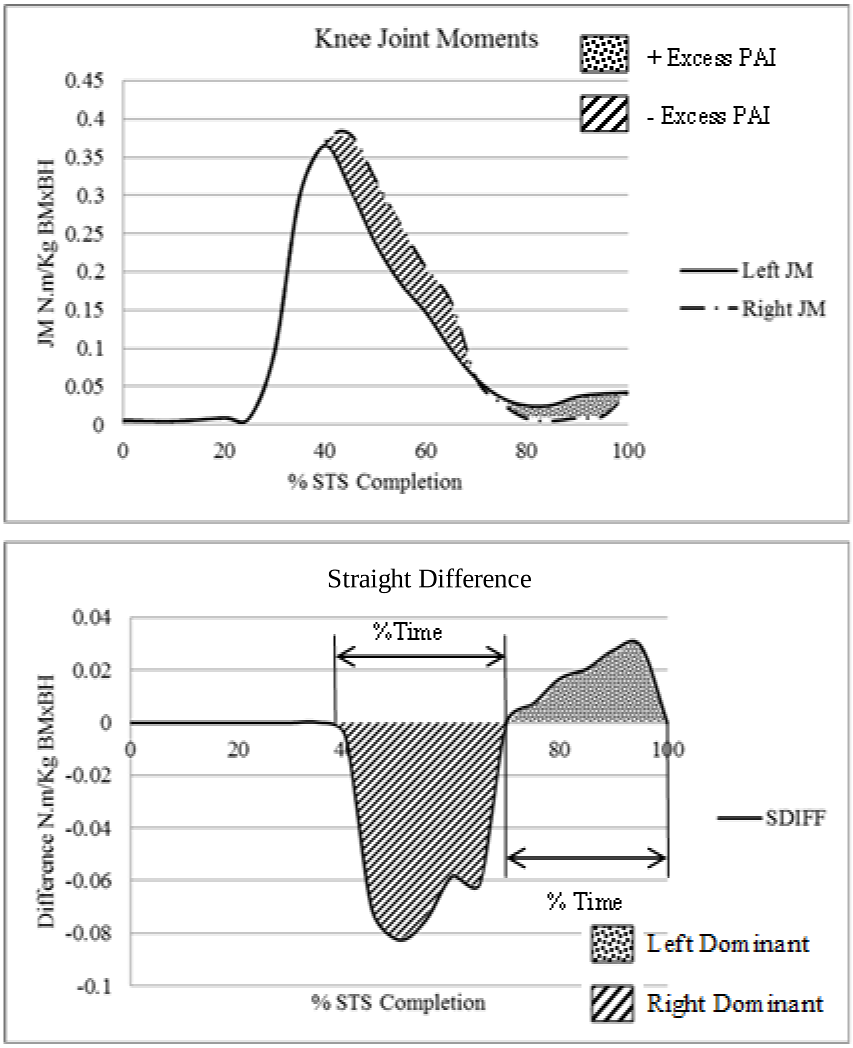

Table 2 Average JM and JP Peak Offest Values and Corresponding P-values

JM and JP are the average joint moment and joint power offset values in %time of the STS cycle. SD is the standard deviation of these values. P-value shows the results from the t-test of first to peak compared to last to peak. $P<0.05$ was assumed to show a significant difference in these mean times

Joint	JM (%)	SD (%)	p-value	JP (%)	SD (%)	p-value
Ankle	3.60	5.15	0.027	12.00	14.30	0.017
Knee	0.80	1.03	0.018	1.00	1.05	0.047
Hip	2.00	4.99	0.118	4.40	7.99	0.049

Figure 3 Straight Difference Plots for Each Participant According to Joint

Where JM, JP and SDIF represent joint moment, joint power and straight difference respectively, units are given in Newton or watts meters per kilogram (Nm/Kg) or (W/Kg) normalized to body mass (BM) and body height (BH). Par # denotes an individual participant's SDIF data.

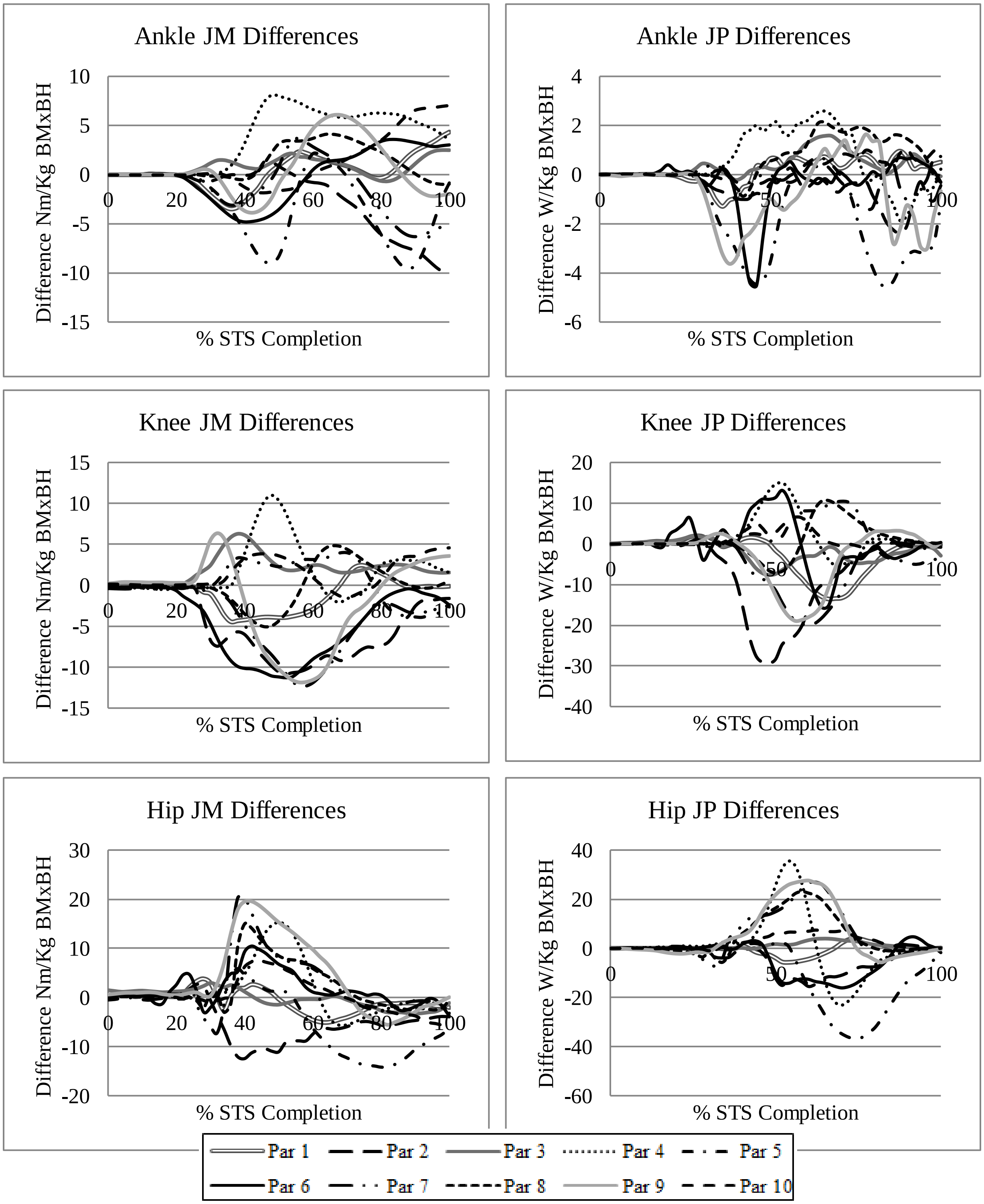

Table 3 Slope Changes in Joint Moment and Joint Power Data

The number of slope changes is organized by participant and joint. JM represents joint moment data and JP, joint power. Groups indicate the number of slope reversal categories seen in the participant. Average and SD show the mean number of slope reversals at each joint and the corresponding standard deviation.

	Number of Slope Reversals													
	Participant	1	2	3	4	5	6	7	8	9	10	Groups	Average	SD
Ankle	JM	3	0	2	1	3	3	3	2	2	1	4	2.00	1.05
	JP	6	6	4	2	3	6	5	2	6	6	5	4.60	1.71
Knee	JM	2	1	2	3	3	1	1	2	2	2	3	1.90	0.74
	JP	2	1	2	2	3	1	1	2	2	2	3	1.80	0.63
Hip	JM	4	1	2	2	2	4	2	2	2	1	3	2.20	1.03
	JP	4	1	3	2	2	4	2	2	2	1	4	2.30	1.06

Figure 4 Positive PAI and PW Plotted Against %Time Positive or Negative

The circles represent the positive PAI (or PW) plot against time the JM SDIF (or JP) remain positive respectively. Since these values are positive, LD is an abbreviation for left side dominant. Inversely the crosses represent the negative equivalents. Since these values are negative, RD is an abbreviation for right side dominant.