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Effect of Initial Knee angle and Arm Facilitation on biomechanics of the Sit-to-Stand movement.*

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***Abstract*— Spinal cord injuries cause loss of muscle function and subsequently reduce independence. Therapeutic interventions such as transcutaneous spinal cord stimulation are increasingly being used to help improve motor functioning however, a comprehensive understanding of the biomechanical elements of movement may help optimize stimulation protocols. Twenty healthy participants completed five sit-to-stand (STS) transitions while initial knee angle and arm facilitation were altered. Electromyography (EMG) activation of four lower limb muscles and centre of pressure dynamics were recorded.**

Acute initial knee angles resulted in a change in duration of phases within the STS, and restrictive arm positioning caused the time to completion to increase (p=0.04). Muscle activation patterns across phases were compared and showed significant differences between phases in both the Tibialis Anterior and Rectus Femoris (p<0.006). Acute initial knee angles were also found to significantly increase Biceps Femoris activation across multiple phases (*p*=0.034).

Altering the starting position and limb movement result in vastly different temporal and muscular strategies to complete the STS. Thus, joint angle and upper limb facilitation should be considered when designing rehabilitative interventions for clinical cohorts.

***Clinical Relevance*— This study quantifies the contribution of musculature and joint kinematics on maintaining balance during the sit to stand transition. Such results may be used to inform targeted rehabilitative training protocols and improve the efficacy of therapeutic interventions such as transcutaneous spinal stimulation.**

I. Introduction

Spinal cord injuries (SCI) result in the partial or complete loss of function of muscles, subsequently impacting independence and quality of life [1]. Treatments and rehabilitative programs tend to rely on assistive devices [2], compensation techniques and specialized training [1]. However, another important therapeutic intervention which is gaining traction as a treatment for those with SCIs is transcutaneous spinal cord stimulation (tSCS).

Therapeutic use of tSCS has shown to generate or augment movement in lower limbs of people with complete and incomplete spinal cord injury, [3], as well as increase trunk stability [4] and improve balance [5]. tSCS may therefore, potentially provide non-invasive therapeutic options to those with SCIs. While studies have focused on the use of tSCS in stationary activities such as standing [3, 5] or sitting [4], research into its application in improving functional mobility is in its infancy. To improve the efficacy of tSCS treatments, the biomechanical elements involved in activities of daily living must be understood to specify optimal tSCS parameters such as stimulation delivery sites and intensities.

The sit to stand (STS) transition, for example, is considered one of the most frequently used activities of daily life and vital for functional mobility and independence [6]. The transference of the centre of mass from a low stable seated position to an upright position with a narrow base of support [7, 8] is a biomechanically complex task involving coordination of all lower limb joints, extensive musculature, and postural control [8]. Failures of the STS movement are often divided into 'step forward,' resulting from the inability to maintain balance at full extension, or 'sit back' failure, often caused by lack of momentum or strength in the lower extremities [9, 10].

Various biomechanical factors such as joint angles also influence the ease of difficulty of the STS transition. When initial knee angle was altered at 10° intervals, more acute knee angles resulted in greater task difficulty and increased time taken to reach full extension [8, 11]. This likely stems from the greater effort needed to transfer weight forwards, as suggested by the more pronounced fore/hind shift in the center of pressure during conditions with smaller initial knee angles [11].

Similarly, the level of engagement of specific muscle groups contributes to the individual's capacity to rise from a seated position. Numerous muscle groups are recruited at specific intervals to maintain stability [12]. Hip extensors decelerate the forward velocity of the center of mass when leaning forward, while the gastrocnemius and tibialis anterior slow and stabilize the center of mass when standing and engaging anticipatory postural adjustments [13, 14].

The aim of this study was to understand the contributions of each element, both individually and in concert, towards the success of the STS transition, and thus allow for the identification of metrics best suited to measure activities of daily living, and inform targeted rehabilitation training protocols.

Figure 1. Illustration of phases of the Sit to Stand transition

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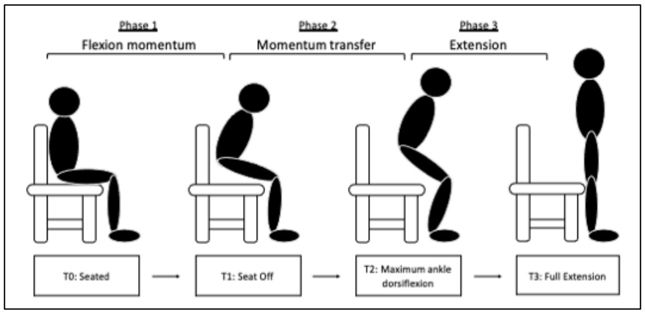

II. METHODS

A. Procedure

Twenty healthy volunteers (10 males, 22–37 years) with no history of musculoskeletal issues completed the STS transition (See Table 1). Participants sat on a height-adjustable chair while starting knee angle was altered (80°, 90°, and 100°) and arms were either crossed or moved freely. Blocks of five repetitions of each condition were carried out, with conditions randomized between blocks. Visual feedback of knee angle was presented to participants to ensure correct positioning for each repetition.

B. Biometric data

Centre of pressure (COP) movement was recorded for each foot at 100Hz using the F-Scan in-shoe pressure sensors, then averaged to report whole body COP (Tekscan Inc, Boston, USA). Joint angles were recorded at 60Hz using the Xsens Awinda system with 17 motion trackers placed across the body as per manufacturers instruction (Xsens MVN Awinda; Xsens, Enschede, Netherlands)(See Fig. 2). Surface electromyography (EMG) was also recorded from the Rectus Femoris (RF), Biceps Femoris (BiF), Soleus (SOL) and Tibialis Anterior (TA) muscles, at 2000Hz using Trigno wireless acquisition system (Delsys Inc., Boston, MA, USA) and transferred to LabChart software (ADInstruments) for processing. A pre-trial isometric maximum voluntary contraction (MVC) protocol was conducted to affirm positioning of the EMG electrodes and determine the maximal MVC for each participant per muscle group. EMG data were bandpass filtered 20-500Hz, zero offset removed, and root-mean-squared (rmsEMG) at a resolution of 20ms. EMG data were normalized and expressed as a percentage of MVC.

C. Data Analysis

The STS motion was divided into three phases based on kinematic data (See Fig. 1). Phase 1: initial trunk movement to seat off, Phase 2: seat off to maximum ankle dorsiflexion, Phase 3 ended when full extension was reached.

Outcome variables included the time to complete the total STS movement and phase durations. COP variables included sway amplitude, velocity, and path length. rmsEMG was calculated for each muscle for each phase. The mean of 5 repetitions for each trial condition was calculated and used for statistical analysis.

TABLE I. DEMOGRAPHIC INFORMATION

	Mean (n=20)	***Standard deviation***
Age (years)	25.4	3.55
Weight (Kg)	71.55	10.61
Height (cm)	175.87	8.62
BMI (Kg/m^2)	22.69	1.87

D. Statistics

The distribution of data was established using a Shapiro Wilks test for normality. A series of two-way ANOVAs were used to examine the effects of knee angle and arm facilitation on STS time to completion (T_c), phase duration, muscle activity and COP. Where significance was observed, post hoc analysis was carried out using Tukey's test. To compare muscle activation across phases a series of One-Way Repeated measures ANOVAs were employed, with Bonferroni correction for multiple comparisons.

III. RESULTS

A. Time to Completion and Phase Duration

Arms crossed significantly increased T_C compared to non-restricted arms (p=0.043). Neither knee angle nor arm facilitation had an effect on Phase 1 duration. However, more acute knee angles were found to have a significant impact on Phase 2 and Phase 3 duration (p<0.001), increasing Phase 2, and decreasing Phase 3 duration. A post-hoc Tukey's multiple comparisons test revealed significant differences in Phase 2 and Phase 3 between 80° vs 100° (p<0.0001) and 80° vs 90° (p=0.025). See Table 2 for phase duration summary.

B. Muscle Activity

Muscle activation across phases was compared using one-way repeated measures ANOVAs. These found a significant difference in the rmsEMG of the TA between all three phases (p<0.0001). Bonferroni's multiple comparison post-hoc tests were used to compare each phase and found rmsEMG to be significantly higher in P1 than P2 and P3, and significantly higher in P2 vs P3 (adjusted p values of 0.0001, 0.0005 and 0.006, respectively). The same is true of the RF, with rmsEMG significantly greater in P1 vs P2, P1 vs P3 and P2 vs P3 (adjusted p values of 0.02, 0.002 and 0.005, respectively). No significant differences were found in the SOL between phases. Although differences in muscle activation of the BiF did not reach levels of significance, there is a trend of maximum activation in Phase 1, followed by decreases in rmsEMG throughout Phase 2 and 3.

In addition, two-way ANOVAs were used to examine the effect of knee angle and arm facilitation on muscle activity across the entire STS and within each phase.

TABLE II. PHASE DURATION AS PERCENTAGE OF TOTAL TIME

Knee Angle	Arms Crossed			Arms Free		
	P1 (%)	*P2 (%)*	*P3 (%)*	*P1 (%)*	*P2 (%)*	*P3 (%)*
100°	27.3 (7.14)	19.3 (10.78)	53.4 (11.46)	30.9 (3.26)	12.4 (4.11)	56.9 (5.26)
90°	30.6 (5.14)	14.5 (5.40)	54.9 (4.51)	30.1 (5.49)	16.2 (7.72)	53.7 (6.24)
80°	28.4 (6.51)	19.8 (9.05)	51.8 (7.46)	29.0 (8.30)	19.7 (8.48)	51.3 (8.88)

Values are reported as mean (SD)

Figure 2. Photograph of equipment used to record movement. 'A' marks several motion trackers which make up the Xsens Awinda system for joint angle detection. 'B' indicates the Tekscan in-shoe pressure sensors, recording the COP movement. Not pictured are the wireless EMG electrodes.

Although there is a trend within the TA and RF of increasing muscle activity with decreasing initial knee angle, the difference did not meet the criteria for statistical significance. However, knee angle was found to have a significant effect on the BiF (p=0.036). Post-hoc analysis showed a significant difference between 80° and 100° (p=0.027), with an overall trend of higher muscle activation with more acute initial knee angle.

Within Phase 1, lower knee angles were found to significantly increase rmsEMG in the BiF (p=0.028), with Tukey's multiple comparison test showing a significant difference between 80° and 100° (p=0.026). Knee angle had the same effect on BiF in Phase 2 (p=0.034), with Tukey's test showing a significant difference between 80° and 100° (p= 0.027). Following the same trend of overall STS, higher rmsEMG was recored in the BiF at more acute knee angles.

Within Phase 3, no significant effect of knee angle or arm facilitation on any muscle activation level was found. However, the interaction of knee angle and arm facilitation did have a significant effect on rmsEMG of the RF (p=0.044). In this case, arms crossed resulted in an increase in rmsEMG of the RF with more acute intitial knee angles, whereas the arms free condition showed no trend of increased rmsEMG as initial knee angle was varied.

C. COP Results

Two-way ANOVAs were carried out to examine the effect of initial knee angle and arm facilitation on the amplitude of anterior-posterior (AP) and mediolateral (ML) COP sway, and AP COP velocity across all three phases. Knee angle was found to significantly influence AP sway amplitude in Phase 1 (p=0.016), such that sway amplitude at 80° was significantly greater than that at 100° (p= 0.012). ML sway amplitude in Phase 1 also increased when knee angles were smaller (p=0.002) and arms used freely (p=0.005). A post-hoc Tukey's multiple comparison test showed the amplitude at 80° to be significantly higher than that at 100° (p= 0.002). Contrastingly, there is a trend in Phase 2 and 3 of the arms crossed condition having a higher ML sway amplitude compared to the arms free condition.

During Phase 3, 80° knee angle was also found to cause significantly greater ML sway amplitude than 100° (p=0.025) and 90° (p=0.01). Lower knee angle was also found to significantly increase the AP COP velocity in both Phase 1 (p =0.018) and Phase 3 and (p =0.048). A post-hoc analysis showed the velocity at 80° to be higher than that at 100° in Phase 1 (p =0.017).

IV. Discussion

The success of STS transition relies on lower limb strength, balance, and neuromuscular control [15]. The study presented here characterizes the contribution of arm facilitation, knee angle and EMG activity on the sit-to-stand transition at various phases of the movement. The main findings of this study show that acute knee angles result in variations in phase duration, and restricted movement of the arms resulted in greater EMG activation in muscles responsible for postural control and stabilization during the extension phase of the movement.

There is a growing body of evidence suggesting the therapeutic efficacy of tSCS in improving functional outcomes during static activities [3-5], however, there is a paucity surrounding dynamic functional activities of daily living. Before tSCS can be applied effectively to aid movement, protocols for optimization of stimulation timing and intensity must be established for specific movements. The sit to stand transition is a biomechanically complex movement with temporally and physically distinct phases, which this study aimed to elucidate.

These findings show a strong link between arm facilitation and time to completion. When arms were crossed against the chest, participants took longer to reach full extension, likely due to the loss of forward momentum generated by arm swing.

Similarly, knee angle impacted phase duration, with the effect particularly notable in Phase 2, the momentum transfer phase, and Phase 3 the extension phase. This increase was most notable when knees were at an 80° angle, and therefore feet were situated further from the body's sitting centre of mass (COM) compared to 100°, where feet are closer to the body's sitting COM. Smaller knee angles, result in a greater distance for the COM to travel before reaching a stable position over the base of support, and completing the extension phase of the STS, subsequently increasing the duration of Phase 2 of the movement [11]. This is reflected in the COP, in particular, the greater AP sway amplitude, as previously reported in respect to COM [13]. The recorded increase of AP COP velocity due to smaller knee angle also explains why T_C was not affected by knee angle. This indicates a reflexive response of participants to achieve stability as quickly as possible.

This effect was compounded when arms were crossed against the chest. Restrictive arm movement has been linked with greater sway, particularly in the AP plane, due to decreased dispersion of the COM [16] or by acting as counterweight shifting weight away from the direction of instability and reducing angular momentum of the body [17, 18]. Therefore, restricting arm movement, perhaps, increased the demand on the TA to ensure stability and balance. This reinforces the argument that arm movement provides a substantial and functionally relevant contribution to dynamic movement in both momentum generation and stability [18].

Muscle activation patterns were also examined throughout the phases of the STS movement. Typically, muscles activate in a predetermined sequence to rise and maintain balance [19]. The anterior movement of the trunk propels the body's COM forward, while knee extensors aided by hip extensors, drive the body upwards [13, 20]. A notable finding of this study is that of the increased TA activation in Phase 1 and dissipation throughout the remaining phases. The RF followed a similar pattern. However, greater activation of RF would be expected during uprising to seat off (Phase 2)[13]. Such results suggest the concurrent activation of trunk flexion and leg extension during initial phases of the STS.

Previously studies reported the soleus to be most active in later stages of the STS, due to its role in postural control and stability [13]. This was not the case in this study, possibly due to issues with electrode placement over the soleus muscle, resulting in high signal-to-noise ratio. Alternatively, some studies define the end of STS as 'stable standing' after full extension [21]. Therefore, it is possible soleus activation is not captured within the phases defined here, which were solely defined by joint kinematic data, unlike previous studies using video motion capture and force plates [21].

This study on a healthy cohort has validated a qualitative protocol which may be used in clinical cohorts, such as those with SCI. However, the results of this research should be interpreted considering its limitations. Although the results of this study provide insight into the biomechanics of the STS transitions, this involved a lean sample size, and a lack of failed STS transitions. Also, the extensive equipment takes a substantial time to set up and calibrate, which participants may find frustrating or tiring.

Future studies may therefore benefit from streamlining the setup to mitigate participant fatigue. While arm facilitation is a significant contributor to the completion of STS, arm usage in this study was binary and did not consider assistive devices for push-off or stabilization, and should be explored in future. The effects of surface stabilization should also be examined in concert with various knee angles, particularly in relation to EMG activation and subsequent changes in COP. Corticospinal excitability through tSCS should be explored in relation to neuroplastic change and potential alterations in functional outcomes, for example H-reflex modulation. The results of this study may be useful in informing tSCS protocols of optimal timing of stimulation to maximize efficacy and to improve movement in clinical cohorts.

The results of this study reaffirm the complex interactions between body components and limb placement, which affect neuromusculature as someone rises from a seated position. Therefore, it is paramount that careful consideration be given to knee angle and arm facilitation when using kinematic, electrophysiological or kinetic data as inputs in any tSCS control system design.

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