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Comparison of peak shoulder and elbow mechanical loads during weight-relief lifts and sitting pivot transfers among manual wheelchair users with spinal cord injury

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Abstract—This study compared shoulder and elbow joint forces and moments between weight-relief lifts (WRLs) and sitting pivot transfers (SPTs) among manual wheelchair users with spinal cord injury (SCI) (N = 13) during biomechanical laboratory assessment. Minimum and maximum values were reported for each triaxial component of the joint force at the dominant shoulder and elbow during SPTs (leading and trailing roles) and WRLs. Peak shoulder flexor and adductor moments, along with elbow flexor and extensor moments, observed during the same period were also analyzed. The SPTs predominantly exposed ($p < 0.001$) the shoulder joints to substantial posteriorly directed forces (leading = –2.6 N/kg; trailing = –3.1 N/kg) compared with WRLs (–2.2 N/kg), whereas superiorly directed forces (2.9 N/kg) were principally sustained ($p < 0.001$) during WRLs compared with SPTs (leading = 1.5 N/kg; trailing = 1.5 N/kg). High superiorly directed forces (3.6 to 3.9 N/kg) were observed at the elbow, which were comparable (p = 0.33) between the two tasks. The peak shoulder flexor (leading = 1.36 N·m/kg; trailing = 1.45 N·m/kg) and adductor moments (leading only = –0.46 N·m/kg), along with the peak elbow flexor moments (leading = 0.24 N·m/kg; trailing = 0.15 N·m/kg), were significantly more elevated ($p < 0.021$) during SPTs than during WRLs. Peak shoulder adductor (–0.46 vs –0.24 N·m/kg) and elbow flexor moments were also more elevated (p = 0.03) at the leading upper limb compared with the trailing one. The peak elbow extensor moments did not differ (p = 0.167) between the two tasks (–0.17 to –0.25 N·m/kg). SPTs exposed the shoulder and elbow joints to greater mechanical loads than WRLs among individuals with SCI.

Key words: activities of daily living, force, kinetics, moment, paralysis, paraplegia, rehabilitation, spinal cord injury, task performance and analysis, upper limb.

INTRODUCTION

Individuals who sustain a complete spinal cord injury (SCI) rely on their upper limbs (ULs) for manual wheelchair propulsion and many other wheelchair-related functional activities, such as weight-relief lifts (WRLs) and transfer tasks [1–2]. Over time, such an increased use of their ULs may augment the risk of experiencing secondary impairments affecting the integrity of the skeletal,

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Abbreviations: 3-D = three-dimensional, ANOVA = analysis of variance, C = cervical, EMG_{max} = maximum electromyographic, LED = light-emitting diode, SCI = spinal cord injury, SD = standard deviation, SPT = sitting pivot transfer, T = thoracic, UL = upper limb, WRL = weight-relief lift.

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muscular, neurological, or vascular structures of the shoulder, elbow, or wrist joints [1–2]. These impairments may, in turn, deleteriously affect ability to perform functional activities and may restrict social participation among individuals with SCI [3–4]. To prevent the development and perpetuation of this potentially damaging cycle, researchers have studied manual wheelchair propulsion extensively and developed precise clinical practice guidelines to protect UL joint integrity among individuals with SCI [1]. Somewhat surprisingly, still a paucity of biomechanical studies focus on WRLs and transfer tasks, although these activities most likely rank among the most demanding wheelchair-related activities for the ULs [1,5–7], and no study has compared these two tasks.

When performing WRLs in a seated position, individuals with SCI generally place both hands on the armrests or on the top part of the tires/hand rims of the wheelchair, slightly in front of the hip joints in a symmetrical position. Thereafter, most individuals slightly bend their head and trunk forward, while flexing and adducting their shoulders and extending their elbows at the same time, to lift their body weight off the seat. WRLs are routinely performed by individuals with SCI in daily life for various reasons. For example, clinical practice guidelines recommend performing WRL every 15 to 30 minutes of sitting and supporting body weight off the seat for at least 30 seconds, ideally for a period of about 2 minutes to bring the tissue oxygen level back to an unloaded level [8]. When individuals with paraplegia performed WRLs, high (>50% EMG_{max}) to moderate (25%–50% EMG_{max}) muscular demands of the latissimus dorsi, sternal pectoralis major, and long head of the triceps have been documented, especially during the lift phase. For those with tetraplegia (SCI at cervical [C]-level C5 to C7) having the capacity to perform WRLs, an increased level of activation is required at the anterior deltoid to produce elbow extension and compensate for the complete paralysis of the triceps brachii [9–11]. Consequently, individuals with tetraplegia (SCI at C5 to C7) have been found to predominantly rely on their shoulder muscles (flexor and adductor) as well as their elbow flexors and wrist flexors when performing WRLs [12]. When these individuals lifted 90 percent of their body weight, the mean peak shoulder and elbow flexor moments were 0.65 and 0.41 N·m/kg, respectively [12]. The corresponding value for the shoulder adduction moment was about 0.55 N·m/kg [12]. When individuals with paraplegia performed WRLs in a wheelchair [5], mean peak shoulder and elbow flexor moments of 0.6 and 0.5 N·m/kg, respectively, were reported. Of greater importance, shoulder and elbow peak absolute resultant moments were found to be more than five and nine times greater, respectively, when WRLs were performed, compared with level manual wheelchair propulsion [5].

When performing sitting pivot transfers (SPTs), individuals with SCI generally place one hand beside the proximal half of the thigh slightly in front of the hip joint (trailing hand) on the initial surface, with the other hand positioned on the target surface (leading hand), far enough away to leave adequate space for the buttocks to land at the end of the transfer [13]. From this position, they habitually flex and rotate the trunk and head forward and sideways while lifting the body off the initial surface and pivoting the buttocks in one motion to the target surface. The SPT terminates when the buttocks land beside the leading hand on the target surface and sitting balance has been secured. On average, individuals with SCI perform 14 to 18 of these transfers a day [14–15]. Typical SPT examples include transferring from a wheelchair to a regular bed, a tub/shower bench, a toilet seat, a treatment table, or a car seat, and vice versa. When individuals with SCI perform SPTs, higher muscular activation is measured during the lift phase of the transfer compared with the pre- and postlift phases for the majority of UL muscles [16]. Moreover, high (>50% EMG_{max})-to-moderate (25%–50% EMG_{max}) muscular demands have been reported at the serratus anterior, latissimus dorsi, supraspinatus, infraspinatus, pectoralis major, anterior deltoid, and long head of the biceps [16]. Contrary to clinical belief, low triceps activity (<25% EMG_{max}) has been found during SPTs. Similar mean muscular activation has also been documented between the leading and trailing ULs during the lift phase of the SPT for many UL muscles [16]. Yet, research recently documented that the trailing UL tended to be exposed to greater peak vertical and horizontal forces than the leading UL when individuals transferred between sitting surfaces of similar heights [17–18]. Under the trailing hand, peak vertical and horizontal forces have been found to reach approximately 50 and 10 percent, respectively, of the total body weight around seat-off during SPTs performed by men with SCI [17–18]. Thereafter, vertical and horizontal reaction forces progressively decrease under the trailing hand during the lift phase of the SPTs as body weight is rapidly lifted and pivoted near the leading hand before the individual lands on the target seat [17–18]. The trailing UL having to counteract the initial flexor momentum, primarily generated by the inertia effect of the axial skeleton (head and trunk segments), may explain the higher peak forces recorded underneath the trailing hand when compared with the leading hand. Interestingly, no mean vertical force difference has been found underneath the leading and trailing hands during the lift phase of SPTs performed between seats of the same height [18]. To date, no study has rigorously documented UL joint forces and moments when individuals with SCI perform SPTs.

The high number of WRLs and of SPTs performed daily among individuals with SCI, along with the high forces and moments experienced at the elbow and shoulder joints while performing these tasks, further supports the need for detailed biomechanical investigations of these functional activities. The main objective of this study was to quantify and compare the triaxial net shoulder and elbow joint forces and shoulder flexor and adductor moments, along with elbow flexor and extensor moments, when the dominant UL played three distinct roles: (1) leading UL during SPTs, (2) trailing UL during SPTs, and (3) lifting UL during WRLs with symmetrical hand position in individuals with SCI. Our main hypothesis was that SPTs would generate higher shoulder and elbow mechanical loads (forces and moments) than WRL and that these loads would be more elevated at the trailing shoulder and elbow than at the leading ones during SPTs.

METHODS

Participants

A convenience sample of 13 right-hand-dominant male volunteers (42.5 ± 9.2 yr [mean ± standard deviation (SD)]; 1.76 ± 0.08 m; 84.0 ± 18.3 kg) with complete motor traumatic thoracic (T)-level SCI (T4 to T11) sustained on average 8.9 ± 10.6 years prior to the laboratory assessment participated in this study. All were able to independently perform SPTs between seats of same heights and WRLs in a seated position without human assistance or technical aid. Of interest, participants completed on average 19 ± 5 SPTs daily. Subjective assessment and objective clinical examinations (passive and active movements, resisted static movements, clinical diagnostic tests, and palpation), as proposed by Magee [19], confirmed that none of the participants presented signs and symptoms of musculoskeletal impairments affecting the trunk or UL joints or had any other condition that might alter their ability to transfer. Ethical approval was obtained from the Research Ethics Committee of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal. Participants reviewed and signed informed consent forms before entering the study.

Experimental Tasks

Participants performed three SPTs between an initial and a target seat, both 50 cm high, to represent typical transfer situations encountered in daily life (**Figure 1(a)**). After, participants completed three WRLs while sitting on a seat 50 cm high while their hands were positioned on resting surfaces set 10 cm higher than the seat (**Figure 1(b)**). Participants were instructed to lift as high as possible and to hold the lift for 3 seconds during WRLs. For the two experimental tasks, we marked the force-sensing surfaces for each participant after a familiarization period to ensure that their foot, buttocks, and hand starting positions would be constant across SPT and WRL trials. A familiarization period allowed each participant to optimize task proficiency within the simulated laboratory environment before recording SPT and WRL trials [20]. We also encouraged participants to use their usual movement strategies, especially in terms of movement amplitude and velocity, when conducting these experimental tasks. The starting position was held constant in all trials of each task for each participant but was not perfectly standardized across participants. However, the starting positions were similar across participants given the restrictions imposed by the experimental setup in terms of foot, buttocks, and hand placement possibilities (instrumented surfaces).

Figure 1.
Overview of laboratory assessment of **(a)** sitting pivot transfers and **(b)** weight-relief lifts.

Reaction Force Recording

To assess SPTs, we used five force-sensing surfaces to quantify the reaction force underneath the feet, buttocks (initial and target seats), and hands (leading and trailing) (**Figure 2(a)**) [18]. The two height-adjustable instrumented chairs were both bolted to the concrete floor, positioned beside one another with a 65° angle separating the two seats. To monitor the reaction forces generated under the hands, we attached an additional separate and detachable width- and height-adjustable hand force plate laterally to each chair. We adjusted these hand force plates to ensure that the width of the seats matched the width of participant's wheelchair. To record the reaction forces during the WRLs (**Figure 2(b)**), we asked participants to sit on the target seat and we raised the height of the right hand force plate attached to it by 10 cm. We moved the initial seat beside the target chair to serve as the left hand surface and raised its height by 10 cm to match the height of the right hand surface. These experimental setups allowed for continuous recording, amplifying, and storing of the resulting reaction forces of each instrumented surface at a sampling frequency of 600 Hz during the entire duration of the transfers. Subsequently, we filtered the forces recorded during these tasks using a fourth-order Butterworth zero-lag filter, with a cutoff frequency of 10 Hz, and resampled at 60 Hz. The *x*, *y*, and *z* components of the reaction forces corresponded to the anteroposterior (F_x), vertical (F_y), and mediolateral (F_z) directions, respectively, within the global coordinate framework of the laboratory (**Figure 2**). This instrumented transfer assessment system has been described at length in a previous study [20].

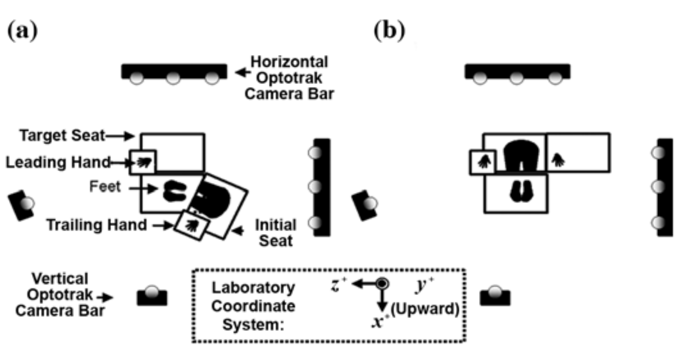

Figure 2.
Transverse view of laboratory setups for **(a)** assessing sitting pivot transfers and **(b)** weight-relief lifts. x^+ = anterior, y^+ = superior, z^+ = lateral.

Kinematics

We recorded kinematic parameters during SPTs and WRLs at a sampling frequency of 60 Hz using an Optotrak motion analysis system consisting of four synchronized camera units (model 3020; NDI Technology Inc; Waterloo, Ontario, Canada) [20–21]. This system tracks the three-dimensional (3-D) coordinates of the three noncollinear skin-fixed light-emitting diodes (LEDs) placed on the pelvis, upper trunk, arms, forearms, and hand rigid segments [20–21]. In addition, two noncollinear LEDs skin-fixed to the clavicle and specific bony landmarks were digitized with a six-marker probe for further definition of articular centers and principal axes of segments [20–21]. We visually inspected all marker trajectories to identify missing marker coordinates and, when possible, interpolated their coordinates using a linear or cubic spline method. The marker coordinates were finally smoothed with a fourth-order Butterworth zero-lag filter using a cutoff frequency of 6 Hz. We used custom-made programs to quantify kinematic parameters (joint angle, velocity, and acceleration) at the shoulder and elbow joints [22–25]. Shoulder flexor-extensor kinematic parameters correspond to the rotation of the longitudinal axis fixed to the arm segment around the transverse axis passing through the left and right glenohumeral joints at the trunk segment (positive toward the right). Shoulder abductor-adductor kinematic parameters correspond to the complement of the angle formed by the longitudinal axis fixed to the arm segment and the transverse axis of the trunk segment when rotating around an axis defined by the cross product of these previous two axes [25]. Elbow flexor-extensor kinematic parameters correspond to the rotation of the longitudinal axis fixed to the forearm segment around the transverse axis passing through the medial and lateral epicondyles of the arm segment [25]. Additional details on the kinematics are available [20–21].

Net Joint Forces and Moments

We inputted the data recorded, the reaction forces measured underneath each right hand, right UL kinematic data, and right anthropometric data into a 3-D inverse dynamic algorithm, performed with a custom-made program developed from Kingait3 software (Mishac Kinetics; Waterloo, Ontario, Canada). We then calculated the net joint forces and moments acting at the shoulder and elbow at all times. To use this approach, we considered the arm, forearm, and hand segments three distinct rigid bodies linked by the shoulder, elbow, and wrist joints, respectively. The net anteroposterior (F_x), vertical (F_y), and mediolateral (F_z) joint forces acting at the shoulder joint were expressed within the arm segment coordinate frame and those at the elbow joint within that of the forearm. These net forces reported for the shoulder and elbow joints were computed using inverse dynamic calculations strictly relying on the externally measured reaction forces recorded under hands. The contribution of muscles forces to joint contact forces has not been determined in the present study. The net shoulder and elbow moments were expressed around the same axes as those previously described to report kinematic parameters with a Jacobian matrix [26]. We were then able to calculate flexor-extensor moments at the shoulder and elbow joints along with abductor-adductor moments at the shoulder joints.

Data Processing

We divided all SPT and WRL data into three phases: prelift, lift, and postlift [18,20–21]. The start of the prelift phase corresponded to the start of the acceleration phase of the head and upper-trunk segments that preceded the lift phase. The lift phase started when the vertical force (F_y) equaled zero at the initial seat and ended when the impact force (F_y) reached its peak value on the target seat for the SPTs or back on the initial seat for the WRLs. The end of the postlift phase coincided with the end of the deceleration phase of these same segments. We further validated the start and end of each phase by verifying the initial and final vertical displacements of the center of mass of the pelvis for all experimental trials. Joint forces and moments were time-normalized to 100 data points per phase for a total of 300 data points for each trial. This time-normalization allowed us to characterize joint forces and moments for the entire duration of the SPTs and WRLs.

Outcome Measures

For each trial, we computed minimum and maximum values of triaxial components of the joint force (F_x, F_y, F_z), which generally represent different force directions for the right shoulder and elbow. We also identified peak net flexor and abductor moments at the shoulder and in flexor and extensor moments at the elbow for each trial. For each participant, we determined these outcome measures for each of the three trials of a given task and averaged to obtain mean values for each participant. All mean force and moment values were normalized against body mass (kilograms) for each participant and reported as Newton per kilogram (N/kg) and Newton-meter per kilogram (N·m/kg), respectively. Outcome measures were normalized to body mass because good correlations ($r > 0.61$) have previously been found between most of the outcome measures and body mass [27].

Statistical Analysis

We calculated descriptive statistics to obtain group means (±1 SD) for all demographic and anthropometric characteristics, clinical data, and outcome measures. For each variable of interest (minimum and maximum joint forces and peak moments), we used one-factor repeated-measures analysis of variance (ANOVA) to determine whether differences existed between the three distinct roles played by the dominant UL: (1) leading role during SPTs, (2) trailing role during SPTs, and (3) lifting role during WRLs with symmetrical hand position. Whenever an ANOVA was found to be significant, we completed Bonferroni tests to locate differences. Two-tailed tests were selected for all statistical analysis, and $p \leq 0.05$ with Bonferroni post hoc correction applied confirmed statistical significance. We performed all statistical analyses using SPSS (SPSS, Inc; Chicago, Illinois) software, version 11.5.

RESULTS

Shoulder and Elbow Joint Forces

At the shoulder joint, the joint forces were oriented posteriorly, superiorly, and medially during the two tasks (**Figure 3**). The posterior peak force was more important ($p < 0.021$) when performing SPTs (leading = –2.64 N/kg; trailing = –3.14 N/kg) than when performing WRLs (–2.19 N/kg) and reached its highest amplitude when the dominant shoulder played a trailing role as opposed to a leading role ($p < 0.001$). The superiorly directed joint force was greater ($p < 0.001$) when performing WRLs (2.91 N/kg) compared with performing SPTs (leading = 1.63 N/kg; trailing = 1.47 N/kg). No significant difference ($p = 0.875$) was found between the leading and trailing roles of the shoulder during SPTs for this force direction. The lateral (0.44 N/kg; $p < 0.02$) and medial (–1.65 N/kg; $p < 0.03$) joint forces were the highest when the dominant UL assured the leading role during SPT. The lateral force was higher ($p = 0.003$) when the right UL played a trailing role during SPT compared with a lifting role during

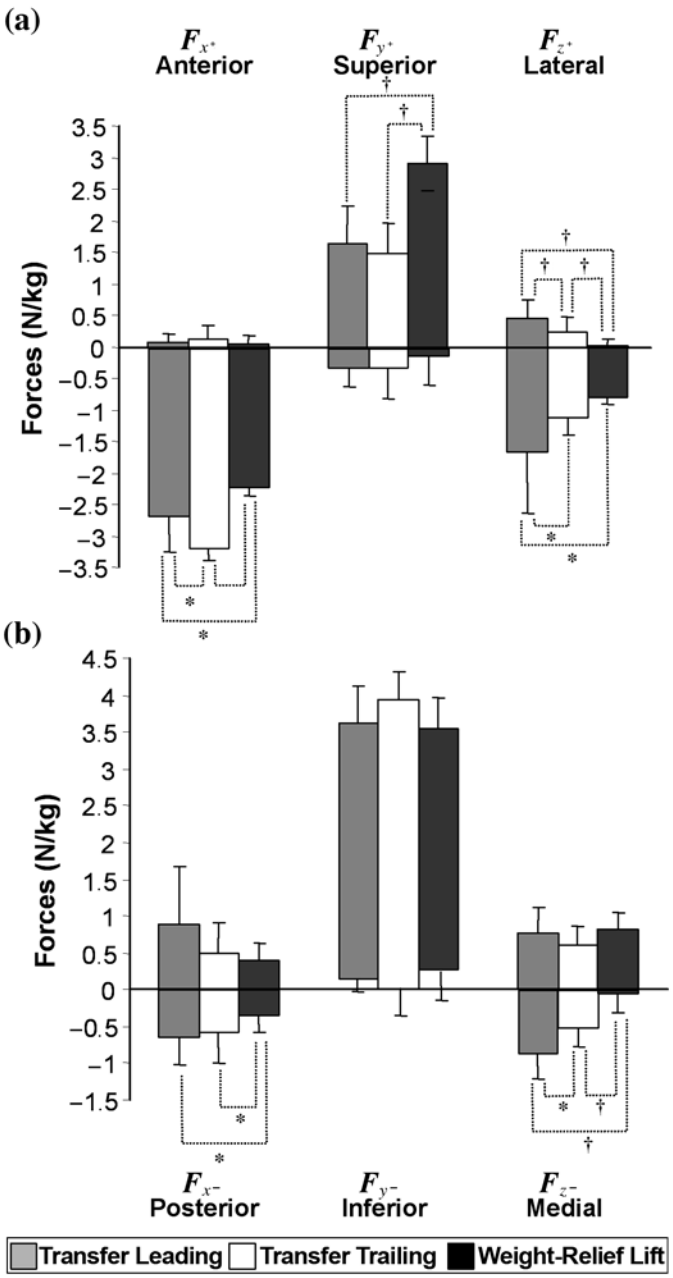

Figure 3.
Bar graphs showing mean ± standard deviation of triaxial component of net forces measured at (**a**) shoulder and (**b**) elbow joints during sitting pivot transfers (leading and trailing role) and weight-relief lifts. x^+ = anterior, y^+ = superior, z^+ = lateral, x^- = posterior, y^- = inferior, z^- = medical. $^*p < 0.05$, $^\dagger p < 0.01$.

WRL, whereas the medial force was similar ($p = 0.108$) when comparing these two roles.

At the elbow, participants sustained substantial superiorly directed forces (3.57 to 3.95 N/kg) across all conditions studied that were accompanied by anteriorly posteriorly and medially laterally joint forces of lower intensity (–0.85 to 0.88 N/kg). No difference was observed between the roles of the dominant arm for the vertical ($p = 0.053$), anterior ($p = 0.069$), or lateral ($p = 0.333$) components. For the posterior and medial forces, peak forces ($p < 0.05$) were always higher when performing SPTs compared with performing WRLs. The peak medial force was also found to be more substantial ($p = 0.023$) at the leading elbow (–0.85 N/kg) compared with the trailing elbow (–0.51 N/kg).

Shoulder and Elbow Joint Moments

The peak shoulder flexion moments were always greater ($p < 0.001$) during SPTs (leading = 1.36 N·m/kg; trailing = 1.45 N·m/kg) than during WRLs (0.75 N·m/kg), whether the shoulder played a leading or a trailing role ($p = 0.171$) (**Figure 4**). The highest shoulder adductor moments (–0.46 N·m/kg) were reached when the dominant UL played the leading role during SPTs ($p < 0.030$). The elbow flexor (0.005 to 0.24 N·m/kg) and extensor (–0.18 to –0.25 N·m/kg) moments were generally of small amplitude, especially when compared with the shoulder flexor moments (>0.75 N·m/kg). The elbow flexor moments

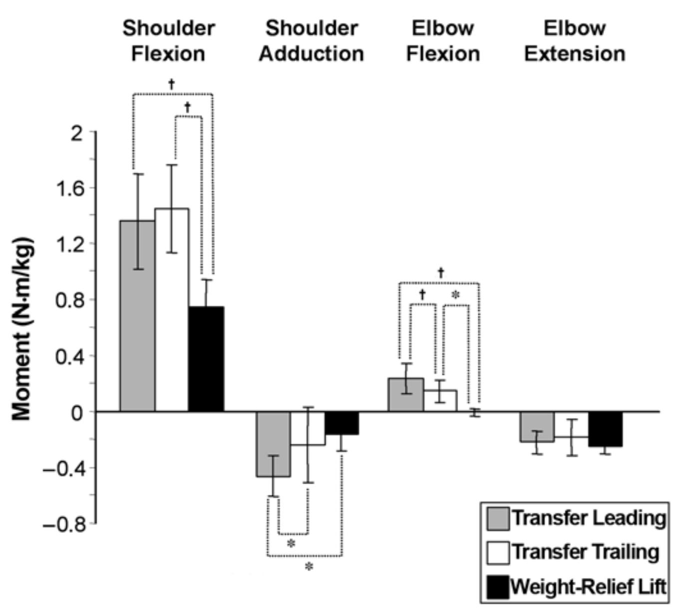

Figure 4.
Bar graphs showing mean ± standard deviation peak net moments measured at shoulder and elbow joints during sitting pivot transfers (leading and trailing role) and weight-relief lifts. $^*p < 0.05$, $^\dagger p < 0.01$.

reached their highest value ($p = 0.030$) when playing the leading role during SPTs. No elbow extensor moment difference ($p = 0.167$) was found across the three different roles played by the dominant UL.

DISCUSSION

This study assessed the joint forces and net moments at the shoulder and elbow when the dominant UL played three distinct roles during functional tasks (SPTs and WRLs) performed by individuals with SCI. Somewhat surprisingly, shoulder and elbow joint forces and moments have never been quantified during SPTs, though this task is performed numerous times daily (frequency) and ranks among the most demanding wheelchair-related activity (intensity) for the ULs [1,5–7]. This article is the first to quantify UL shoulder and elbow joints forces and moments during SPTs among individuals with SCI using a biomechanical approach and also the first to compare shoulder and elbow joints forces and moments between different roles played by the UL during SPTs and WRLs among individuals with SCI. Overall, this study revealed that the performance of SPTs and WRLs imposed different shoulder and elbow challenges, especially in joint forces and moments.

Shoulder and Elbow Joint Forces

At the shoulder, researchers have focused mostly on the vertical force in the past when assessing functional activities among individuals with SCI, hardly considering the other force directions. Based on the current results, such an interest may be motivated by WRLs triggering superiorly directed shoulder forces that largely exceeded the amplitudes found in the horizontal direction. In fact, the superiorly directed component calculated at the shoulder during WRLs exceeded those observed during SPTs, regardless of the role played by the UL during SPTs. However, the posterior shoulder joint forces were greater during SPTs than WRLs, with the value reached at the trailing shoulder surpassing the value of the leading shoulder.

At the shoulder, the combination of the high superiorly and posteriorly directed joint force components may indeed be detrimental, especially for the glenohumeral joint. The vertical shear stress may result in an upward translation of the humeral head, which may exacerbate the development of an impingement of subacromial structures against the overlying acromion, particularly in the presence of narrowed humeroacromial space or osteophytes beneath the acromioclavicular joint. The posterior shear stress may also be detrimental, leading to the development of posterior instability, capsulolabral pathology, and tendinitis (supraspinatus, infraspinatus, teres minor) [7,28–32]. The repetitive microtrauma associated with these substantial forces may also precipitate joint degenerative changes [33–34].

For the elbow joint forces, the superiorly directed joint forces clearly dominated and were found to be similar across the three distinct roles played by the dominant UL. For this joint, this component strongly predominated the other directions and this predominance should be kept in mind. The considerable amount of superiorly directed joint forces compresses this joint and may explain, in part, some secondary musculoskeletal impairments, for example, compression neuropathy of the ulnar nerve [35]. The anteroposterior and mediolateral force components, although thought to be of lesser importance than the superiorly directed forces, also require consideration because they may contribute to the development of other secondary impairments, especially if elbow instability has developed [36].

Shoulder and Elbow Joint Moments

For the shoulder joint moments, the finding that the flexor and adductor moments were more elevated during SPTs than during WRLs is greatly relevant for this study. The shoulder flexor moments at the dominant UL were found to be more elevated during SPTs than WRLs, with the trailing shoulder reaching slightly higher values than the leading shoulder. Such shoulder flexor moments reinforced the key role played by the pectoralis major and anterior deltoid muscles during SPTs as previously documented [16]. Significant differences were also observed for the adductor moments. Aside from the SPT values exceeding the values measured during WRLs, a difference was also found between the roles played by the UL during SPTs. The highest adductor moments reached at the leading shoulder during SPTs corroborates the high EMG (electromyographic) activity previously recorded at the sternal pectoralis muscle, which also was more elevated at the leading UL than the trailing UL, during SPTs [16]. This finding may be further explained by the substantial concentric shoulder adductor moment occurring at the leading shoulder, whereas an eccentric shoulder adductor moment is observed at the trailing shoulder as the body weight is moved toward the target seat during SPTs [20]. In fact, eccentric muscle contractions have been shown to require lower muscular effort (lower EMG) to generate a given force when compared with static or concentric contractions [37]. The lower net shoulder adductor moment observed at the trailing shoulder may also have been counteracted to some extent by the static and concentric shoulder abduction cocontractions (abductor moment) developed at the trailing shoulder to optimize joint stability and to push body weight toward the target seat, as suggested by a previous EMG study [16]. One should consider that possibly the substantial shoulder flexor and adductor effort required during SPT, may come close to or even slightly exceed, the maximum force-generating capability of these muscle groups [38–39]. In this case, an individual with SCI possibly may not be able to independently perform SPTs, and weakness of these shoulder muscle groups should be considered a limiting factor. Another possibility would be to have this individual modify his movement strategy to compensate for the muscle weakness. The investigation of a larger group of participants with various levels of SCI in the future may allow us to determine the influence of the level of SCI on the shoulder moments and the use of compensatory strategies during functional UL tasks. Such a study would be of great interest because EMG activity of shoulder and elbow muscles was previously found to be influenced by the level of SCI during WRLs [40]. Finally, one should remember that the risk of developing secondary musculoskeletal impairments at the shoulder may be increased because the substantial muscle contractions needed to generate these moments further elevate the shoulder joint forces.

For the elbow moments, comparable extensor moments were generated across the different roles played by the dominant UL. Somewhat surprisingly, the need for a flexor moment during SPT was confirmed and may certainly challenge the clinical assumption that only an extensor moment is crucial when SPTs are performed. This flexor moment at the elbow was found to be of greater importance when the UL acted as the leading UL rather than the trailing UL, which may confirm its pulling role during SPTs as previously documented [20–21]. This particular finding partly corroborates the results emerging from EMG studies revealing moderate bicep activation and low tricep activation during SPTs [16] and adds to the findings reporting negligible biceps activation during WRLs among individuals with paraplegia [40]. Note that the substantial shoulder flexor moments, previously discussed, may also induce a dynamic interaction extension torque fixing the elbow in a quasistatic position or contributing to its extensor movement (adjacent joint) during transfers [9–11]. One should also consider that these relatively low elbow net moments may mask substantial agonist and antagonist effort because they only represent net joint moments. This finding supports the need for EMG studies in the future to better understand these tasks.

Clinical Relevance

Based on current and previous studies, SPTs can be ranked as one of the most mechanically demanding (forces and moments) routinely performed wheelchair-related activity among individuals with SCI [1,5–7]. For this reason, caution is warranted when rehabilitation professionals initiate SPT training, especially during the initial intensive rehabilitation process. During this period, the use of human assistance or a technical aid (e.g., sliding board) when individuals with SCI are performing SPTs may be encouraged until these individuals reach sufficient strength-generating capability to potentially minimize UL mechanical loads. However, this hypothesis remains to be verified.

Since the results of the current study revealed substantial shoulder and elbow moments, muscle strength assessment and retraining are warranted. As for the UL strengthening program, many rehabilitation professionals continue to direct considerable attention at the triceps and latissimus dorsi muscles when conducting strength training among individuals with SCI as is traditionally encouraged [13,41]. Such a strengthening program has a limited chance of improving the individual's ability to perform SPTs or preserving shoulder and elbow integrity. Instead, based on the current results, strengthening of the shoulder flexor and adductor muscles, for example, should be encouraged in the future. Note that an optimal level of stabilization is essential at the scapula to maximize the force-generating capability of these two key muscle groups acting at the shoulders (scapulohumeral joints) [42]. Hence, specific muscles key in stabilizing the scapulothoracic functional articulation (serratus anterior, rhomboids, upper trapezius, levator scapulae, pectoralis major) may also need to be strengthened [43–44]. Finally, the importance of preserving the agonist and antagonist muscle strength balance at the shoulders should not be neglected.

Readiness to initiate SPT training should not be based solely on the ability to perform WRLs in clinical practice. Although this ability may be considered key in indicating SPT performance [13,41], one should remember that substantial mechanical demand differences (forces and moments) have been highlighted between these two tasks in the current study. Nonetheless, SPTs remain unquestionably more demanding (net moments) than WRLs.

Confirming a general rule for a specific UL to play the role during SPTs would also seem hazardous without a specific diagnosis of the musculoskeletal impairment based on the differences reported between the leading and trailing shoulders and elbows. In light of the current results, alternating the role that each UL plays when SPTs are performed between even surfaces may allow to evenly distribute shoulder and elbow mechanical loads experienced over the course of a day, as recently recommended [1].

Finally, the use of alternative methods when pressure-relief skills are taught should also be encouraged because they may considerably reduce UL mechanical loads while being just as effective [8]. In fact, leaning forward or side to side, for example, has proven an effective alternative to WRLs to preserve skin and soft-tissue integrity among individuals with SCI [8].

CONCLUSIONS

This comprehensive biomechanical study is the first to objectively document shoulder and elbow forces and moments when individuals with SCI complete independent SPTs using a self-selected technique and is the first to compare SPT and WRL tasks. The results confirm that SPTs are among the most mechanically challenging wheelchair-related activities, in shoulder and elbow joint forces and moments, routinely performed by individuals with SCI. More precisely, the performance of SPTs and WRLs was found to predominantly expose the shoulder joints to substantial posteriorly and superiorly directed forces, respectively, whereas the elbow was found to sustain elevated superiorly directed forces when these two tasks were performed. The shoulder flexor and adductor moments, along with the elbow flexor moments, were also higher during SPTs than during WRLs. The elbow extensor moments were similar when SPTs or WRLs were performed. These results highlight the key role of UL muscle strength during SPTs, especially at the shoulder, and confirm the need to develop task-specific strength training protocols for individuals with SCI to reach optimal shoulder strength before initiating transfer training. Transfer aids might also be useful for reducing UL mechanical requirements, although this hypothesis remains to be verified. Overall, this study helps develop evidence-based data for a better understanding of SPTs and may allow refinement of clinical practice guidelines targeting the preservation of UL integrity among individuals with SCI.

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