Research article

Upper limb joint kinetics of three sitting pivot wheelchair transfer techniques in individuals with spinal cord injury

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Study design: Repeated measures design.

Objective: This study compared the upper extremity (UE) joint kinetics between three transfer techniques.

Setting: Research laboratory.

Methods: Twenty individuals with spinal cord injury performed three transfer techniques from their wheelchair to a level tub bench. Two of the techniques involved a head–hips method with leading hand position close (HH-I) and far (HH-A) from the body, and the third technique with the trunk upright (TU) and hand far from body. Motion analysis equipment recorded upper body movements and force sensors recorded their hand and feet reaction forces during the transfers.

Results: Several significant differences were found between HH-A and HH-I and TU and HH-I transfers indicating that hand placement was a key factor influencing the UE joint kinetics. Peak resultant hand, elbow, and shoulder joint forces were significantly higher for the HH-A and TU techniques at the trailing arm ($P < 0.036$) and lower at the leading arm ($P < 0.021$), compared to the HH-I technique.

Conclusion: Always trailing with the same arm if using HH-A or TU could predispose that arm to overuse related pain and injuries. Technique training should focus on initial hand placement close to the body followed by the amount of trunk flexion needed to facilitate movement.

Keywords: Activities of daily living, Secondary impairments, Biomechanics, Rehabilitation, Shoulder pain

Introduction

Among full-time manual wheelchair (MWC) users, being able to propel and transfer independently are key factors to achieving and maintaining an independent lifestyle. Therefore, any loss of upper extremity (UE) function can severely affect overall functional mobility and independence. Research has found that on average a person with spinal cord injury (SCI) performs 15–20 transfers per day.¹ Based on the frequency of transfers and the weight-bearing forces involved,

transfers are believed to contribute to the development of UE pain. The prevalence of UE pain among persons with SCI is around 30–60% at the shoulder, 22–45% at the elbow, and 40–66% at the wrist.² Research has also suggested that the onset of UE pain is functionally and economically equivalent to an SCI of higher neurological level.³ Because transfers are essential to daily living and independence, learning how to perform them in ways that reduce joint forces and moments may prevent or delay the onset of pain and help preserve UE function overtime.

Sitting-pivot-type transfers (SPTs) are most common among individuals with SCI who are unable to stand

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unsupported.⁴ To prepare for the transfer, individuals usually scoot forward in their chair and place their feet on the ground. One hand is placed on a target surface (leading hand) while the other hand is placed on a part of the WC or a grab bar (trailing hand). From this starting position the individual begins the transfer; the arms lift the body off the WC and shift it laterally while controlling the pivoting motions of the trunk (e.g. flexion, rotation, and elevation) and lower body about the feet.¹ The transfer is complete when the person lands on the target surface and regains seated postural stability. In theory, if the head–hips relation, i.e. the aforementioned movement strategy, is used, more momentum can be generated to facilitate moving the body. Research on a related task (pressure relief pushups) suggests that the forward-flexed trunk position is ideal for engaging sternal pectoralis major and latissimus dorsi muscles.⁵ This muscle activation may help transfer the body weight (BW) between the leading arm (arm reaching to new surface) and trailing arm (arm left behind during move to new location) with less loading of the glenohumeral joint, thereby reducing the risk of rotator cuff impingement.^{5,6}

Poor transfer techniques have been associated with loss of function of the UEs.⁷ Evidence regarding optimal transfer technique is limited.^{1,2,8} In a recent study, we investigated the biomechanics of several different SPT transfer techniques which varied on two factors: hand placement and trunk flexion in an able-bodied group of subjects.⁹ The SPT techniques were derived from the literature, which described two general movement strategies used when performing long sitting transfers (e.g. transfers with the legs extended in front of the body): *rotational strategy* (head moves in an opposite direction to the pelvis) and *translational strategy* (head and pelvis move simultaneously in the same direction).¹⁰ The *rotational strategy* is analogous to what clinical practice refers to as the “head–hips” relation. Three techniques were compared in the study. Two techniques used the head–hips relation where the trunk was forward flexed and the leading arm was abducted and away from the body (HH-A) and again with the leading arm close to the body and internally rotated (HH-I). The third technique mimicked the translational strategy where the trunk remained upright and the leading arm was abducted and away from the body (TU). We found that the head–hips transferring techniques reduced superiorly directed forces across all three UE locations, in comparison to the trunk upright (TU) style of transferring. Although there was a reduction in superior forces with the head–hips transferring techniques, the moments at

the shoulder (flexion/extension and external rotation) were higher in comparison to the TU strategy.

The purpose of this study was to study the effects of these same three techniques on the UE kinetics in a cohort of MWC users with SCI.

Methods

Subjects

This study received ethical approval from the Department of Veterans Affairs Institutional Review Board. After reading and providing informed consent, 20 subjects (19 male, 1 female), volunteered to participate. The inclusion criteria were: SCI at the C4 level or below that occurred over 1 year prior to the start of the study, unable to stand and weight bear through the legs, use a MWC as a primary mode of mobility (e.g. 40 hours per week), able to independently transfer to/from a MWC without human assistance or assistive devices, over 18 years of age, and free from UE pain that influenced their ability to transfer.

Experimental protocol

Participants used their personal WCs to transfer to and from a bench. For all transfers, the WC was positioned and secured at a comfortable angle from an adjustable height tub bench as shown in Fig. 1. The bench was adjusted to be level with the WC seating surface. The instrumented transfer setup contains three force plates (Bertec Corporation, Columbus, OH, USA), one beneath the WC, one beneath the tub bench, and one located below the feet.¹¹ The WC and bench were secured to the platform. A steel beam attached to a six-component load cell (Model MC5 from AMTI, Watertown, MA, USA) was positioned to simulate a WC armrest. Reflective markers were placed on the subjects C7, T3, and T8 vertebrae, sternum, xiphoid, right and left acromion processes, radial and ulnar styloid processes, lateral epicondyles, and third metacarpal–phalangeal joints (Fig. 2). The coordinates of the markers were recorded based on a global reference frame using a 16-camera three-dimensional (3D) motion capture system (Vicon Peak, Lake Forest, CA, USA). Several anthropometric measurements were recorded including: BW, axillary, shoulder, elbow, wrist and fist circumference, upper arm and forearm length.

All transfers began with the left arm leading and moving the body from the WC to the bench. The three transfer techniques were performed in a random order. Prior to performing each of the transfer techniques, subjects were shown an instructional video on how to complete the transfer. For the HH-A transfer, subjects were

Figure 1 WC (left) and tub bench (right) shown secured to the aluminum mounting plates of the base frame. The custom interface consists of the load cell and a beam that can be positioned anywhere along base frame.

instructed to place their left hand on the far circular target on the bench, right hand on a target placed on the force beam, and transfer leaning their trunk forward as far as possible, moving their buttocks towards a large target on the bench while moving their head in the

opposite direction (Fig. 3A). The HH-I transfer required the same instructions except that the left hand was placed on a near circular target on the bench, with the left arm internally rotated (Fig. 3B). For the TU transfer, subjects were instructed to place their left hand on the far

Figure 2 Marker locations used to define the segments of the head, trunk, arm, and forearm.

Figure 3 Still photos from the transfer instruction video for the two types of head-hips relation transfer and translational transfer.¹² (A) Transfer 1: Head-hips with arm extended. (B) Transfer 2: Head-hips with arm close. (C) Transfer 3: Trunk upright with arm extended.

target of the bench, right hand on the target on the force beam, and transfer with their TU moving their buttocks towards the large target on the bench while moving their head in the same direction (Fig. 3C). Subjects practiced each technique on average two times, until they were confident they could perform the transfer based on instructions provided. Each transfer technique was performed three times and kinetic and kinematic data were recorded synchronously at 360 and 60 Hz, respectively, for the length of the transfer. Subjects rested about 5 minutes in between each transfer trial while the data were being saved and verified. Subjects were frequently reminded during testing that they could take breaks or have additional rest time as needed.

Data analysis

Subjects' anthropometric measures were used to estimate the segment inertial properties based on Hanavan's mathematical model.¹³ In this model, the hand is modeled as a sphere and the forearm and upper arm are both modeled as frustums of right circular cones. Segment center of mass locations were also estimated using the methods described by Hanavan.¹³ Kinetic data were down-sampled to 60 Hz, to align with the kinematic data. Both kinematic and kinetic data

were filtered with a fourth-order zero-lag Butterworth filter (cut-off frequency of 5 and 7 Hz, respectively).

Kinetic, kinematic, and anthropometric data were entered into an inverse dynamic model to calculate the 3D net shoulder and elbow joint forces and moments. The inverse dynamic model used was based on the general rigid-link segment model using a Newton-Euler method and a variable degree of freedom body coordinate system.¹⁴ The local coordinate systems were approximated using the guidelines established by the International Society of Biomechanics.¹⁵

The vertical reaction force from the force plate under the bench and the grab bar were used to determine the start (absolute value of vertical force >0 at the grab bar and bench) and the end (determined prior to the generation of a large spike in the vertical force at the bench) of the transfer. The SPT was delineated into three phases: pre-lift, lift, and descent. The vertical forces from the force plate under the tub bench, WC, and the grab bar (WC side) were superimposed onto one plot to analyze the phases of transfer. Trunk motion, represented by the C7 and T3 markers, were added to the force data to assist with the delineation of phases of transfer.¹⁶

Key biomechanical variables

Analysis was conducted for transfers from the WC to tub bench. For each trial, 3D component and net resultant forces were calculated for the shoulder, elbow, and hand for both arms. Flexor/extensor, abduction/adduction, and internal/external rotation moments at the shoulder, flexor/extensor moments at the elbow and wrist were calculated for both leading and trailing arms. In addition, net resultant forces underneath each hand were time-normalized to the percentage time of the lift phase. Net resultant forces underneath the feet were collected on a subset of the sample ($n = 11$) as another force plate was added to the transfer system after the study had started. Trunk linear and angular velocities for flexion and axial rotation were computed with the center of mass defined for the upper trunk using the right/left acromion and the xiphoid markers.¹⁷ The maximum and minimum of the all variables were identified for the lift phase of the transfer. Maximum values of trunk flexion, leading shoulder elevation angles, and distance of the third metacarpal on the leading hand from global zero (as indicated in Fig. 2) were identified for the pre-lift phase of the transfer and used to test for instruction adherence. Transfer duration was determined from the beginning of the pre-lift to the end of descent phase. Variables were computed using Matlab[®] (Mathworks, Inc., Natwick, MA,

USA) and averaged over the three trials for each transfer technique.

Statistical analysis

Group means and standard deviations were computed for all outcome measures. A one-way repeated measures analysis of variance (ANOVA) was used to compare the resultant foot forces, trunk flexion, trunk linear/angular velocities, leading shoulder abduction, leading hand position, and transfer duration across the three techniques. A two-way within subjects ANOVA was used to evaluate technique differences between the leading and trailing arm biomechanical variables. Because the emphasis of the study was on technique differences, the main effects of technique and interaction effects of arm and technique were further assessed using simple pairwise comparisons and a *post hoc* Bonferroni correction (adjusted level of significance based on *a priori* number of combinations of interest). The statistical tests were performed using SPSS statistical software (SPSS Inc., Chicago, IL, USA), with the level of significance set to 0.05.

Results

Demographics

Of the 20 participants who took part in the study, 18 (17 male and 1 female) could complete all SPT techniques. Data were missing for one out of the three techniques for the two persons who were excluded from the analysis. Of the two individuals, one could not physically complete one of the techniques (HH-I) and for the other person the data were unobtainable due to technical difficulties with the setup. The group of participants consisted of six individuals with low-level paraplegia (T9–L1), six individuals with high-level paraplegia (T2–T9), and six individuals with tetraplegia (C5–C7). The group mean (standard deviation) of age, height, weight, and years since injury were 36.8 ± 10.5 years, 1.7 ± 0.4 m, 76.2 ± 20.0 kg, and 13.7 ± 7.6 years, respectively.

Instruction adherence

The peak trunk flexion angles were significantly higher for the head–hips techniques (HH-A: $51.48 \pm 14.41^\circ$ and HH-I: $48.74 \pm 12.85^\circ$) compared to the TU ($35.48 \pm 13.57^\circ$) technique ($P = 0.001$ and $P < 0.001$, respectively). The leading hand was positioned significantly further away for the HH-A (1.74 ± 0.08 m) and TU (1.73 ± 0.08 m) techniques compared to the HH-I (1.56 ± 0.08 m) technique ($P < 0.001$). Leading shoulder abduction angles were not significantly different across techniques: HH-A ($71.59 \pm 13.26^\circ$), HH-I ($70.14 \pm 15.22^\circ$), and TU ($66.96 \pm 3.47^\circ$). These

findings affirm that the techniques varied on namely: trunk flexion and hand placement.

Technique comparison

Overall, the group mean time and weight-normalized resultant hand force loading curves for each technique show the forces at the trailing hand were relatively constant through the lift phase for the HH-I and TU techniques while a distinct rise in force can be observed for the HH-A transfer (Fig. 4). At the leading hand across all techniques, there was an increase in the loading curve during the lift phase (Fig. 4). Maximum upper trunk torsion velocity was significantly higher for the head–hips techniques (HH-A: $24.24 \pm 22.43^\circ/\text{second}$ and HH-I: $30.51 \pm 32.07^\circ/\text{second}$) compared to the TU ($4.64 \pm 16.63^\circ/\text{second}$) technique ($P < 0.001$). No significant differences were observed for net resultant foot force (% body weight) across the three techniques – HH-A: 27.77 ± 15.77 , HH-I: 24.99 ± 14.51 , and TU: 25.77 ± 14.45 . The transfer duration was significantly longer for the HH-A (2.6 ± 1.7 seconds) technique compared to the TU (2.1 ± 1.4 seconds) technique, $P < 0.001$. The HH-I technique lasted 2.3 ± 1.3 seconds. Statistical differences in the shoulder, elbow, wrist, and hand kinetics for the techniques have been summarized in Table 1 and are described in more detail below.

Shoulder

Peak shoulder internal rotation moment was significantly lower for the HH-I technique compared to the HH-A ($P = 0.002$) and TU ($P = 0.009$) techniques (Table 2). Peak shoulder adduction moments in the trailing arm were significantly lower when transferring with the TU technique compared to the HH-A ($P = 0.010$) and the HH-I techniques (Fig. 5; $P = 0.021$). Peak posterior forces were significantly lower when transferring with the TU technique compared to the HH-I technique (Table 2; $P = 0.042$). Peak lateral forces were lower at the trailing shoulder when transferring with the HH-I technique compared to the other techniques (HH-A: $P = 0.03$ and TU: $P = 0.004$; Fig. 6). Peak resultant forces were significantly lower at the trailing arm, for the HH-I technique compared to the HH-A ($P = 0.014$) technique. At the leading shoulder, the peak resultant forces were significantly lower for TU compared to HH-I ($P = 0.003$).

Elbow

Peak elbow flexion and extension moments were similar across all techniques (Fig. 7). Peak superior forces at the elbow were significantly lower for HH-A compared to TU ($P = 0.002$; Table 2). Transferring with the TU technique resulted in significantly lower peak posterior

Figure 4 Group mean and standard deviation of the resultant hand forces (% BW) across the techniques for the trailing and leading hands. (A) HH-A; (B) HH-I and (C) TU

Table 1 Summary of the significant comparisons of peak UE joint reaction force and moment across the taught techniques

	HH-A	HH-I	TU
<i>Biomechanical variables</i>			
<i>Main effect of technique</i>			
Shoulder internal rotation moment	Higher*	Lowest* ⁺	Highest ⁺
Shoulder posterior force	Higher	Highest*	Lowest*
Elbow superior force	Lowest*	Higher	Highest*
Wrist flexion moment	Higher	Lowest*	Highest*
<i>Technique and trailing arm</i>			
Shoulder adduction moment	Highest*	Higher ⁺	Lowest* ⁺
Shoulder lateral force	Higher*	Lowest* ⁺	Highest ⁺
Shoulder resultant force	Higher*	Lowest*	Highest
Elbow resultant force	Higher*	Lowest* ⁺	Highest ⁺
Hand superior force	Higher*	Lowest* ⁺	Highest ⁺
Hand resultant force	Higher*	Lowest* ⁺	Highest ⁺
<i>Technique and leading arm</i>			
Shoulder resultant force	Higher	Highest*	Lowest*
Elbow posterior force	Highest*	Higher ⁺	Lowest* ⁺
Elbow lateral force	Higher	Lowest*	Highest*
Elbow resultant force	Higher*	Highest* ⁺	Lowest ⁺
Hand superior force	Higher*	Highest* ⁺	Lowest ⁺
Hand medial force	Highest*	Lowest* ⁺	Higher ⁺
Hand resultant force	Higher*	Highest* ⁺	Lowest ⁺

*⁺Significant differences between the pair-wise comparisons of techniques, $P < 0.05$.

Table 2 Significant main effect technique differences mean ($\pm$ standard error) of the peak UE moments and forces

Moment (Nm)		Technique differences averaged across both arms		
		HHA	HH-I	TU
Shoulder	Internal rotation	37.10 (4.45)*	24.69 (4.75)*,†	41.21 (6.03) ⁺
Wrist	Flexion	35.78 (9.91)	5.36 (7.77)*	44.10 (9.55)*
Force (N)				
Shoulder	Posterior	162.40 (13.90)	185.05 (20.82)*	147.65 (12.63)*
Elbow	Superior	128.27 (11.23)*	135.90 (12.24)	167.47 (12.50)*

*,†P < 0.05.

forces at the leading elbow, compared to both head–hips techniques ($P < 0.008$; Fig. 7). Peak lateral forces at the leading elbow were significantly lower for HH-I compared to TU ($P = 0.013$; Fig. 8). At the trailing elbow, peak resultant forces were significantly lower for HH-I in comparison to TU and HH-A ($P < 0.036$). In contrast, at the leading elbow, the TU and HH-A techniques resulted in significantly lower peak resultant forces compared to the HH-I technique ($P < 0.021$).

Wrist and hand

Peak wrist flexion moment was significantly lower for HH-I ($P = 0.003$) compared to TU (Table 2). Peak superior forces were significantly lower at the trailing hand for HH-I compared to the other techniques ($P < 0.015$; Fig. 9). Peak superior forces at the leading

hand were lower for HH-A and TU compared to HH-I ($P = 0.001$ for both). Significantly lower peak medial forces at the leading hand were observed for HH-I compared to HH-A ($P < 0.001$; Fig. 9) and TU ($P < 0.014$; Fig. 9). The HH-I technique resulted in significantly lower peak resultant forces at the trailing hand compared to the other two techniques ($P < 0.02$). The peak resultant forces at the leading hand were significantly lower for HH-A and TU compared to HH-I ($P < 0.005$).

Discussion

This is the first study we know of to explore how different trained SPT techniques affect upper limb biomechanics in a mixed group of MWC users with tetraplegia and paraplegia. In our previous study with the able-

Figure 5 Mean ($\pm$ standard errors) of the 3D component moments at the shoulder across the techniques.

Figure 6 Mean ($\pm$ standard errors) of the peak 3D component forces at the shoulder across the techniques.

bodied subjects, the head-hips techniques reduced superior forces at all the joints. Looking across arms and techniques (Tables 1 and 2) in this study, none of the techniques reduced the force and moment components at all three joints. The differences found

between the earlier study and this study were expected given that the subjects in the first study were able-bodied and naive to transfers. This study uncovered more tradeoff effects across the techniques in this cohort which varied by joint and arm.

Figure 7 Mean ($\pm$ standard errors) of the peak flexion and extension moments across the wrist and elbow for the techniques.

Figure 8 Mean ($\pm$ standard errors) of the peak 3D component forces at the elbow across the techniques.

Technique effects at the shoulder: component forces and moments

Performing HH techniques entails forward flexion of the trunk and anterior translation of the shoulders causing a shift of the center of mass forward (anterior with respect to the spine).^{5,18} Increasing the distance

between the pivot hand (leading arm) and the body's center of mass theoretically would increase the moment arm resulting in an increase in moments about the shoulder.¹⁹ Our data followed this theory to some degree, as significantly larger shoulder adduction moments were generated at the trailing shoulder when

Figure 9 Mean ($\pm$ standard errors) of the peak 3D component forces at the hand across the techniques.

transferring with the head–hips techniques (HH-A and HH-I) compared to the TU technique. However, significantly higher internal rotation moments were generated for the two techniques where the hands were placed further away from the body (HH-A and TU) when compared to the HH-I technique. It follows that despite the differences in trunk motion, having a larger distance between the leading and trailing hands led to higher internal rotation moments. So, one technique tradeoff regarding the shoulder moments was that the amount of trunk motion appeared to have a greater influence over the adduction moments at the shoulder, whereas hand placement appeared to have more influence over the shoulder internal rotation moments.

The peak superior shoulder force most often associated with impingement, or compression of the rotator cuff within the subacromial space, was not significantly reduced with any one of the techniques. However, significantly higher posteriorly directed force was found for the HH-I technique for both arms compared to the HH-A and TU transfer. This could be a source of concern as higher peak posterior and lateral shoulder forces have been linked to magnetic resonance imaging abnormalities of the coracoacromial ligament.²⁰ These same abnormalities have also been associated with narrowing of the supraspinatus outlet and rotator cuff tears.²¹

While larger posterior forces occurred with the HH-I technique, it had smaller trailing arm lateral forces in comparison to HH-A and TU. This finding suggests that using a “near” hand position requires less lateral force to shift bodyweight between the two arms while maintaining postural stability during the transfer.¹ As there were no significant differences found in any of the peak shoulder component forces between the HH-A and TU techniques, the observed differences in the posterior and lateral force components at the shoulders can be attributed to the differences in hand placement.

Technique effects at the elbow: component forces and moments

When the trunk was more upright, we saw a significant increase in superiorly directed force at the elbow across both arms compared to the HH-A. Thus, it appears that flexing forward when the arms are further away from the body helps to circumvent large superior forces at the elbow. A decrease in superior forces at the elbow could potentially minimize the risk of developing ulnar nerve compressive neuropathy at the joint.²² Similar to Gagnon *et al.*,²³ we also found that the posterior peak force was a dominating component force at the elbow during SPTs, which was significantly larger in the

leading arm for both head–hips techniques compared to the TU technique. This is likely due to the extended position of the humerus and increased elbow flexion that occurs when the trunk is forward flexed.²⁴ Peak lateral forces at the leading elbow for the HH-I technique were small in magnitude (1.8 ± 31.68) and significantly lower than the TU technique (Fig. 9). In summary, for the elbow the amount of trunk flexion had a greater influence than hand placement over the more predominant force components (e.g. posterior and superiorly directed forces). The combination of a flexed trunk and hands close to the body reduced leading side elbow lateral forces.

Technique effects at the wrist and hand: component forces and moments

Larger wrist flexion moments were generated for the TU and HH-A techniques compared to the HH-I technique which points to the “far” hand placement having a larger influence over the wrist flexion moments than the amount of trunk motion. These results imply that a greater demand on the forearm muscles is needed to generate forces and/or stabilize the wrist during transfer motions when the arm is further away from the body. The main clinical concern regarding the wrist joint during transfers, however, is the combination of high force and the peak wrist extension angles that exceed active physiological ranges of motion, particularly when a flat palm is used on the transfer surface.^{25,26} Large excursions of the wrist are detrimental due to the inherently unstable bony anatomy associated with the wrist, which also increases the risk of peripheral neuropathy of the median nerve.^{25,27–29} Carpal tunnel syndrome, which is highly prevalent among WC users, results in elevated pressure in the carpal tunnel when the wrist is in a full active flexion or active extension.^{29,30} The peak superior forces were significantly higher at the trailing hand for the TU and HH-A transfers than the HH-I transfer, yet superior forces were significantly lower at the leading hand for the TU and HH-A transfers than the HH-I transfer. Medial hand forces were also higher for the TU and HH-A transfer at the leading hand than the HH-I transfer. These findings suggest that hand positioning over the amount of trunk flexion has a greater influence on the peak component forces recorded under the leading and trailing hands.

Technique effect across all three joints: peak resultant forces

Although there were many tradeoffs in the component forces and moments at each joint and arm, the peak

resultant forces (Fig. 7 and Table 1) for the trailing and leading arms were not significantly different between HH-A and TU. However, several significant differences were found in the peak resultant forces between the HH-A and TU techniques with respect to the HH-I technique. Both HH-A and TU had significantly higher peak resultant forces at the trailing arm and significantly lower peak resultant forces at the leading arm compared to HH-I across both arms at all three joints (Fig. 7). The HH-I showed a more balanced resultant force loading across the two arms. These results suggest that using a “near” leading hand placement is a key factor to balancing the distribution of resultant forces across the upper limb joints. Because the forces are higher, trailing with the same arm if using HH-A or TU could predispose that arm to overuse related pain and injuries. Therefore, one must consider existing UE function and condition (e.g. using the stronger arm or less painful arm as the trailing arm) when adopting or choosing one of these transfer techniques (HH-A or TU). Knowledge of the technique tradeoffs can help a person with choosing which technique may be better in light of existing pathologies and which arm should play the role of leading or trailing.

Other technique differences

The transfer duration of the HH-A technique was significantly longer in comparison to the TU technique, which was likely due to having to flex the trunk to generate the momentum to transfer. In comparison, the TU technique was a quicker lateral shift of the body. Although not significant, the HH-A technique tended to have the largest LE weight bearing among the techniques. We found that the LE's bore close to 25% of BW, which corroborates with previous literature.^{1,31,32} These results reiterate the importance of the LE's to reducing UE joint loading and to achieving dynamic postural stability (e.g. enlarged base of support) during transfers.²

Clinical implications

This study found that overall hand placement during transfers had a greater effect on the UE kinetics than did the amount of trunk flexion. The techniques that involved placing the leading hand further away from the body resulted in greater peak shoulder internal rotation moments (both arms), peak lateral shoulder forces (trailing arm), peak wrist flexion moments (both arms), and uneven amounts of peak hand, elbow, and shoulder resultant force loading between the trailing and leading arms compared to the technique with closer-to-the-body leading hand placement (HH-I).

Keeping the leading hand close to the body during the head–hips motion however increased peak posterior shoulder forces, which may predispose individuals to developing shoulder pathology overtime. The two techniques involving more trunk flexion elevated the amount of peak adduction moment at the trailing shoulder and the peak superior forces at the leading elbow. If the overarching goal is to reduce the total amount of force acting at the joints, then technique training among individuals with SCI ought to focus first on the initial hand placement followed by the amount of trunk flexion needed to facilitate the movement.

Some things to keep in mind with hand placement is that the hands form the outer edges of the base of support, so placing the leading hand closer shrinks the base of support resulting in a less posturally stable position and greater reliance on muscles around the shoulder (e.g. deltoids and rotator cuff) and the elbow (e.g. triceps) to lift and pivot the body.²⁴ If balance or upper limb strength is impaired, a greater distance away may be needed to increase postural stability. This is where the head–hips motion can be useful to help increase stability when the hands are close by lowering the height of the center of mass and facilitating the engagement of the larger more powerful thoracohumeral muscles like the pectoralis major, latissimus dorsi, and serratus anterior.

Certainly, an important objective of a transfer technique should be to minimize internal joint loads. However, there may be other factors to consider from an individual's perspective, such as time it takes to perform the transfer along with how efficiently the transfer can be performed. A transfer technique that would result in higher shoulder joint loading may be adopted by WC users if it facilitates a faster or more efficient transfer, particularly if they are free of pain in that joint. Facing more complex transfer environments (e.g. car transfers, amusement park rides, recreational equipment, etc.) or using compensatory strategies in the presence of pain or fatigue, may lead to implementing a higher force technique. Future studies need to consider not only how technique alone affects upper limb loading during transfers but also the circumstances around which the transfer is occurring (e.g. type of environment, time pressures, etc.) and personal factors (e.g. fear, desires, pain levels, etc.) When presented with various options to place the hands (grab bars, arm and back rests, and so on), hands should be positioned as low as possible in the same plane as the buttocks to maximize the recruitment of the larger thoracohumeral musculature³³ and a hand grip should

be used if one is available, or the fingers should drop off the forward edge of the surface being transferred to and from.²

Limitations

A constraint of the experimental setup was that all transfers began with the left arm leading. The participants in our study were a seasoned cohort of MWC users with an average of 14 years post-SCI and were probably well accustomed to adapting to various environmental situations and doing transfers in both directions. In fact, results from a prior study with a similar cohort showed that muscle demands across the UEs did not vary between preferred versus a non-preferred directions of transfer, irrespective of the UE dominance.¹⁹ While our data indicate that our seasoned cohort were able to execute the taught techniques well, there may be large differences between their usual techniques and the taught techniques. Future work will analyze subjects' usual techniques and assess how similar their biomechanics are to the taught techniques and if it is possible to classify their usual technique into one of the taught techniques. This type of analysis may reveal a new technique (or multiple techniques) that were not evaluated in this study and unveil additional movement strategies that best minimize forces and moments during SPTs. In addition, the pre-assigned target locations did not account for differences in anthropometry between subjects (e.g. limb lengths) which may have affected the amount of loading that occurred at the "near" versus "far" targets.

Conclusion

This study found tradeoffs in the magnitudes of joint force and moment that occurred at the upper limb joints between the transfer techniques. The amount of loading seemingly depended mainly on hand placement more than trunk flexion. Keeping the leading arm close to the body during the head-hips motion balanced the amount of UE joint forces across both leading and trailing arms. Future studies are needed to understand the factors that influence the choice of technique, which techniques to use for different kinds of environments and situations, and which techniques are better long-term.

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Disclaimer statements

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