Linking Wheelchair Kinetics to Glenohumeral Joint Demand During Everyday Accessibility Activities

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Abstract— **The aim of the study was to investigate if push-rim kinetics could be used as markers of glenohumeral joint demand during manual wheelchair accessibility activities; demonstrating a method of biomechanical analysis that could be used away from the laboratory. Propulsion forces, trunk and upper limb kinematics and surface electromyography were recorded during four propulsion tasks (level, 2.5% cross slope, 6.5% incline and 12% incline). Kinetic and kinematic data were applied to an OpenSim musculoskeletal model of the trunk and upper limb, to enable calculation of glenohumeral joint contact force. Results demonstrated a positive correlation between propulsion forces and glenohumeral joint contact forces. Both propulsion forces and joint contact forces increased as the task became more challenging. Participants demonstrated increases in trunk flexion angle as the requirement for force application increased, significantly so in the 12% incline. There were significant increases in both resultant glenohumeral joint contact forces and peak and mean normalized muscle activity levels during the incline tasks. This study demonstrated the high demand placed on the glenohumeral joint during accessibility tasks, especially as the gradient of incline increases. A lightweight instrumented wheelchair wheel has potential to guide the user to minimize upper limb demand during daily activity.**

I. Introduction

The incidence of shoulder pain in manual wheelchair users has been reported to range from 42% [1] to 66% [2]. Rotator cuff muscle injury is most commonly observed, with a significantly higher prevalence reported in manual wheelchair users in comparison to aged matched controls [3] Rate of rotator cuff injury is associated with increasing age and length of time of wheelchair dependency [4].

Glenohumeral (GH) joint health is dependent on maintenance of stability of the humeral head in the glenoid fossa. This stability is achieved largely by activity of the rotator cuff. [5]. The external forces applied to the upper limb during manual wheelchair propulsion have been shown to cause supero-medially oriented joint contact forces [6]. Therefore, a high level of rotator cuff activity is required during manual wheelchair propulsion to maintain stability of the GH joint. Rotator cuff injury is associated with ageing and repetitive loading [5] demonstrating the risk of sustained manual wheelchair use.

Wheelchair users must tackle a number of difficult footway conditions daily as they push from A to B. Previous research highlights increased upper limb demand during cross-slope [7] and incline propulsion [8]. Inclines have been shown to require an increase in both muscle activity [9] and GH joint contact force [6] compared to level propulsion. Therefore, there is a need to measure on a more regular basis the effect of these different obstacles and how people overcome them.

With the utilization of wireless inertial measurement and surface electromyography sensors in addition to a newly designed lightweight instrumented wheelchair wheel, our study presented and tested a method of biomechanical assessment of manual wheelchair propulsion that could be used in any environment. We hypothesized that GH joint demand and therefore injury risk would increase as the force application required to complete the task increased.

II. Methods

A. Participants

7 male SCI subjects participated in the study (SCI level range T5-L1), mean age 42.7 years, mean weight 83.1 kg, mean time since injury 8.9 years. Potential participants were excluded if they reported shoulder pain during propulsion or a history of major shoulder surgery. The study was approved by the National Health Service Research Ethics Committee (14/LO/0542).

B. PAMELA Facility & Equipment

The study was completed at University College London's Pedestrian Accessibility and Movement Environment Laboratory (PAMELA). PAMELA houses a modular platform that can be adjusted to simulate different surface profiles (Figure 1). For this study participants were required to complete 4 different propulsion tasks; level, 2.5% cross slope (instrumented side on the down slope), 6.5% incline and 12% incline.

Push-rim reaction forces were measured with the SenseWheel (Movement Metrics, London, UK), a lightweight instrumented wheelchair wheel. The SenseWheel consists of 3 small load cells distributed at 120° around the handrim and between the handrim and the wheel. Each load

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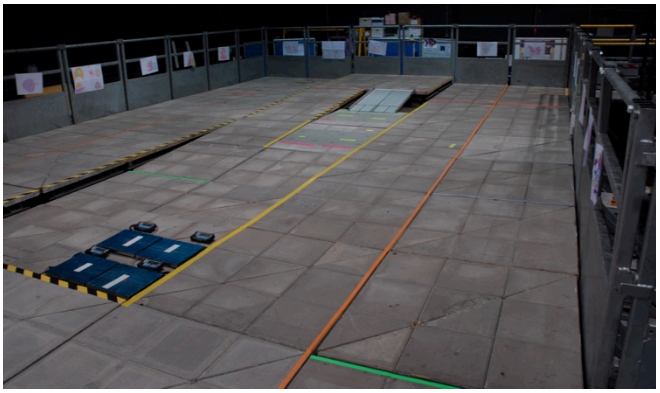

Figure 1: Photo showing the Pedestrian Accessibility movement Environment Laboratory set-up

cell has a ϕ10mm diaphragm within which the electronics are housed. The SenseWheel measures the three components of force Fx, Fy and Fz, and axial torque Tx applied at each load cell and transmits this wirelessly to a laptop. Data were sampled at 50Hz, and calculated reaction forces were applied to the radio carpal joint of the musculoskeletal model. In addition, push rate, % push phase and peak and mean resultant force were calculated.

Trunk and left upper limb kinematics were measured using the XSens MTw inertial measurement system (XSens Technologies, NL). Sensors were attached to the thorax, humerus and forearm and aligned to the anatomical reference system. Data were sampled at 50Hz, and the Euler angles to animate the model coordinates derived from the rotation matrix that determined the relative position of the XSens units either side of the joint.

Surface Electromyography (sEMG) was recorded from the Anterior Deltoid (AD), Pectoralis Major (PM) and Infraspinatus (IS) muscles using the Delsys TrignoTM System (Delsys Inc, MA, USA). Data were sampled at 2000Hz, then full wave rectified and low pass filtered with a cut-off frequency of 5Hz. For each muscle the data collected during the wheelchair propulsion tasks were normalized to the peak value gained from functional Maximal Voluntary Isometric Contraction (MVIC) tests [10]. Peak and mean normalized EMG values were calculated for each of the 4 tasks.

III. Musculoskeletal Model

Measured joint kinematics and push rim reaction forces were applied to an adapted OpenSim model of the upper limb and trunk named ‘Dynamic Arms 2013’, a version of the Stanford VA Upper Extremity Model [11] accessed at www.simtk.org. The model consists of rigid bodies representing the trunk, upper arm, forearm and hand and was constrained to allow trunk lean, 3 degrees of freedom at the GH Joint and flexion/extension at the elbow joint. The actuator set comprised 29 muscles crossing the GH and elbow joints. A reserve actuator was added to the thorax ground joint; otherwise all other model muscle properties were maintained. The model was manually scaled to participant characteristics. The muscle forces to generate joint torques were calculated using the OpenSim (Version 3.1) static optimization analysis, which utilizes an objective function that minimizes muscle activation. The results of the static optimization analysis were used to calculate GH joint contact force during a representative push phase for each of the conditions. The peak and mean resultant GH joint contact force were calculated.

IV. Data Analysis & Statistics

Propulsion parameters, kinematics, sEMG and GH joint contact forces were calculated from a representative push for each of the 4 propulsion tasks. Tests of between task differences were completed using a repeated measure ANOVA. When the results were significant, the Bonferroni post hoc test was applied and results reported to demonstrate differences in measures relative to the level propulsion task. For tests of correlation for each of the 4 tasks, where data were normally distributed Pearson’s correlation coefficient was calculated, otherwise Spearman’s correlation coefficient was calculated. Statistical significance was set at $p<0.05$.

V. Results

Propulsion parameters were significantly affected by task, with significant increases in both peak and mean resultant propulsion force between level and 2.5% cross slope, 2.5% cross slope and 6.5% incline and 6.5% incline and 12% incline (Figure 2). As required force application increased, % push phase also increased, significantly so for both incline tasks. Push rate also increased, but increases were not significant. The participants demonstrated a greater trunk flexion angle as the propulsion tasks became more challenging, significantly so for the 12% incline task. As a result of this, maximum elbow joint flexion angle increased significantly in both incline tasks. There were no significant differences in thoraco-humeral angle across the tasks.

Peak and mean AD muscle activity increased across tasks, with a significantly greater peak activity during the 12% incline task (Figure 3). Peak and mean PM activity increased across tasks, with a significantly greater peak activity during the 12% incline tasks and significantly greater mean activity during both incline tasks. Peak and mean IS muscle activity were greater in both incline tasks, with a significantly greater mean activity during the 12% incline task.

Peak and mean resultant GH joint contact forces increased as the propulsion tasks became more challenging (Figure 4). Peak resultant GH joint contact force was

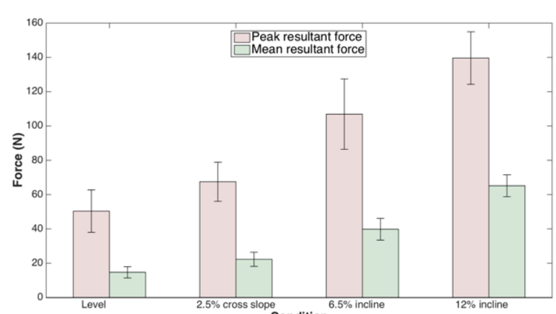

Figure 2: Peak resultant and mean resultant propulsion forces for each of the 4 conditions. Error bars show +/- 1 standard deviation

significantly greater for both incline conditions and mean

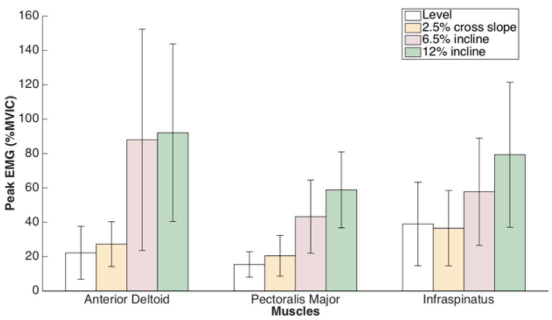

Figure 3: Peak EMG values as a percentage of maximum voluntary isometric contraction. Error bars show +/- 1 standard deviation.

resultant GH joint contact force significantly greater for the cross slope and both incline conditions.

There was a positive correlation between peak resultant propulsion force and peak resultant GH joint contact force during each of the tasks (Figure 5). This correlation was strong during the level task (r = 0.73) and moderate during the 12% incline (r = 0.39). There was also a positive correlation between peak resultant propulsion force and peak IS muscle activity during each of the tasks. This correlation was strong during the level (r = 0.76) and cross slope tasks (r = 0.85) and moderate during the 6.5% incline (r = 0.41).

VI. Discussion

The results demonstrated an increased GH joint demand as the propulsion tasks became more challenging, in terms of propulsion forces, muscle activity levels and GH joint contact forces.

Propulsion forces: Both peak and mean resultant propulsion forces were significantly greater in the 2.5% cross slope than the level task. The peak resultant propulsion value 67.48N is in line with previous data which reported a peak resultant propulsion force of 62.8N on a treadmill set at approximately 5% cross slope [12]. Both peak and mean resultant propulsion forces were also significantly greater in the incline tasks than the level propulsion tasks, with a peak value of 106.9N (13% body weight) in the 6.5% incline and 139.63N (17% body weight) in the 12% incline. These results closely match previous results of 13% body weight in ~5% incline and 17% body weight in ~10.5% incline during a treadmill test [13]. Higher values of peak resultant propulsion force have been reported in another study of treadmill incline propulsion, with the greatest value reported 205.1N during a 12.5% incline task [14].

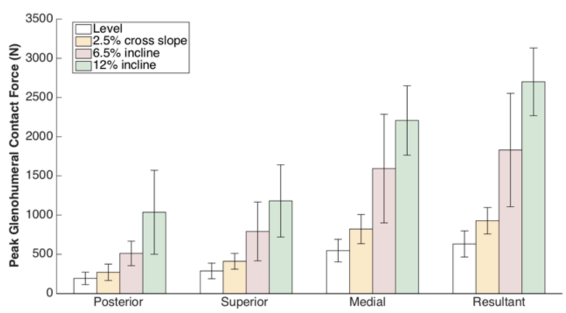

Figure 4: Peak GH contact forces in the posterior, superior and medial planes as well as the resultant contact force across the 4 conditions. Error bars show +/- 1 standard deviation.

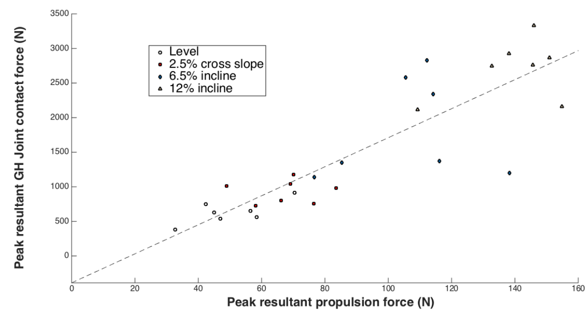

Figure 3: Relationship between the peak propulsion force and the peak resultant contact force occurring at the GH joint.

1) *Muscle activity*

Both peak and mean muscle activity levels increased as the propulsion task became more challenging. The 2.5% cross slope and 6.5% incline tasks did not result in a significant increase in peak muscle activity in any of the muscles tested. Muscle activity levels were significantly greater in the 12% incline task for peak AD (92.10%) and PM (58.85%) and mean IS activity levels (52.21%). Previous studies have demonstrated similarly high levels of muscle activity during equivalent incline treadmill propulsion, including AD (68%) and PM (101%) [15].

2) *GH joint contact forces*

Both peak and mean GH joint contact forces increased as the propulsion tasks became more challenging. Peak GH joint contact force during the 2.5% cross slope was not significantly greater than the level task. Both peak and mean GH joint forces were greater in both the incline conditions when compared to the level propulsion condition. Despite the simplifications in the musculoskeletal model used in this study, including a fixed scapulo-thoracic joint, the GH joint contact force results were similar to those previously reported. A previous study investigated shoulder joint contact forces during treadmill propulsion at different intensities [16]. This study reported a maximum GH joint contact force of 1400N during a task with a peak resultant propulsion force of 69.4N. Another study reported GH joint contact forces during level propulsion and incline propulsion (~8% incline)[6]. Peak GH joint contact force during level propulsion was 702N, similar to the results from the level propulsion task in this study (631.97N). The peak GH joint contact force during the 8% incline was 2555N, in between the values from this study of 1829.87N (6.5% incline) and 2700.50N (12% incline).

3) *Clinical impact*

In this study, shoulder muscle activity level and GH joint contact forces were measured to quantify GH joint demand during wheelchair propulsion. Although negotiating the 2.5% cross slope required a significantly increased propulsion force, there was not a significant increase in GH joint demand. Both incline conditions resulted in significant increases in GH joint demand, particularly during the 12% incline task. IS muscle activity increased, due in part to its contribution to external rotation during the push phase [17] but also due to its role as part of the rotator cuff muscle group, which works to stabilize the humeral head [18]. The IS muscle is used in this study as a measure of rotator cuff activity. When highly active, as in the push phase of wheelchair propulsion, sEMG measurement of IS activity is known to be accurate [19], whereas for the other rotator cuff muscles it is not [20]. The rotator cuff is known to degenerate with age and excessive loading [5], so with increased time of wheelchair use it is apparent that rotator cuff injury may occur, and a vital stabilizing mechanism for the GH joint may be lost. Further repetitive wheelchair use is likely to exacerbate the problem, leading to the secondary effects of rotator cuff damage including degenerative joint conditions, which have been observed in manual wheelchair users [21].

Across the different propulsion tasks, despite the small number of participants there were positive correlations between propulsion forces and GH joint contact forces and IS muscle activity levels. There exists a potential benefit of using a lightweight instrumented wheelchair wheel capable of transferring propulsion data to a mobile device, to track propulsion characteristics and upper limb demand during day-to-day propulsion activities. Strategies can then be implemented to minimize peak forces, and therefore injury risk.

VII. Limitations

Propulsion forces were only measured on one side. Bilateral analysis would have been beneficial, with previous research showing asymmetry, particularly during cross slope propulsion [22]. The musculoskeletal model was limited in that the GH joint was modeled with a fixed scapula and the superior radio-ulnar and radiocarpal joints were locked in a neutral position. These limitations were dictated by the method of kinematic analysis used, and the fact that model did not include musculature for the scapulo-thoracic joint

VIII. Conclusion

This study shows that it is possible to identify markers of GH demand using push-rim kinetics across a number of accessibility tasks. The results of the study demonstrate the importance of measuring wheelchair propulsion during functional tasks. It has shown it is possible to measure the kinetics of everyday pushing using the new lightweight instrumented wheelchair wheel. This has the potential to track upper limb demand during day-to-day propulsion activity, and inform strategies to reduce injury risk.

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