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Short communication

Propulsion biomechanics do not differ between athletic and nonathletic manual wheelchair users in their daily wheelchairs

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ABSTRACT

The purpose of this study was to investigate whether athletic and nonathletic manual wheelchair users (MWU) display differences in kinetic and kinematic variables during daily wheelchair propulsion. Thirty-nine manual wheelchair users (athletic n = 25; nonathletic n = 14) propelled their own daily living wheelchair on a roller ergometer at two submaximal speeds for three minutes (1.11 m s^{-1} and 1.67 m s^{-1}). A 10 camera Vicon motion capture system (Vicon, Motion Systems Ltd. Oxford, United Kingdom) collected three-dimensional kinematics of the upper limbs and thorax at 200 Hz during the final minute of each propulsion trial. Kinetics, kinematics and kinematic variability were compared between athletic and nonathletic groups. Kinematic differences were investigated using statistical parametric mapping. Athletic MWU performed significantly greater physical activity per week compared to nonathletic MWU (920 ± 601 mins vs 380 ± 147 mins, respectively). However, no significant biomechanical differences between athletic and nonathletic MWU were observed during either propulsion speed. During the 1.11 m s^{-1} trial wheelchair users displayed a stroke frequency of 53 ± 12 pushes/min and a contact angle of 92.5 ± 16.2°. During the 1.67 m s^{-1} trial the mean stroke frequency was 64 ± 22 pushes/min and contact angle was 85.4 ± 13.6°. Despite the hand being unconstrained during the recovery phase the magnitude of joint kinematic variability was similar across both glenohumeral and scapulothoracic joints during recovery and push phases. To conclude, although athletic MWU participate in more physical activity per week they adopt similar strategies to propel their daily living wheelchair. Investigations of shoulder pain and dailywheelchair propulsion do not need to distinguish between athletic and nonathletic MWU.

1. Introduction

Shoulder pain is a common complaint in manual wheelchair users (MWU); however, it is uncertain if athletic MWU who engage in wheelchair sports are at greater risk of developing shoulder pain than nonathletic MWU (Curtis and Dillon, 1985; Finley & Rodgers, 2004; Fullerton et al., 2003). Athletic MWU may be at increased risk of acquiring overuse injuries due to the higher frequency of propulsion performed for sporting activities as well as activities of daily living (ADL) (Heyward et al., 2017). However, the increased levels of physical activity and greater strength/muscle mass may have a protective effect for athletic MWU (Fullerton et al., 2003). Although both populations rely on a daily wheelchair it is unclear if athletic and nonathletic MWU should be viewed as distinct groups when investigating the association between shoulder pain and daily propulsion (Heyward et al., 2017). Therefore, establishing how athletic and nonathletic MWU propel their wheelchairs can elucidate this gap in knowledge.

Studies exploring daily wheelchair propulsion biomechanics have largely focused on nonathletic MWU (Collinger et al., 2008; Moon et al., 2013; Walford et al., 2019). Previous studies have primarily characterised propulsion via mean spatiotemporal and kinetic measures (Boninger et al., 2002; Rice et al., 2009). A higher stroke frequency, magnitude of force and reduced push rim contact (contact angle) have been associated with shoulder pain development (Boninger et al., 2005; Sawatzky et al., 2015). The presence of abnormal scapular (dyskinesis) and glenohumeral kinematics have also been implicated in shoulder pain development due to their direct influence on rotator cuff and biceps tendon stress (Ludewig & Cook, 2000) and has been observed during daily propulsion in nonathletic MWU (Morrow et al., 2011; Raina

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et al., 2012; Zhao et al., 2015). In contrast, very few studies have explored the biomechanics of daily propulsion in athletic MWU. Recent work from our laboratory (Mason et al., 2018) noted that wheelchair rugby athletes with tetraplegia display comparable mean scapular kinematics during daily propulsion to previously reported nonathletic studies (Morrow et al., 2011; Raina et al., 2012; Zhao et al., 2015). However, it is unclear if similarities would still be observed across a broader set of biomechanical variables, in an athletic population from a variety of sports and a broader range of impairments to nonathletic populations.

As daily propulsion is a highly repetitive cyclical task, biomechanical investigations should quantify the inter-cycle variability of parameters associated with shoulder pain (Hamill et al., 2012; Sosnoff et al., 2015). Joint kinematic variability quantifies how much an individual modifies their joint orientations from cycle to cycle. Previous studies identified that MWU with shoulder pain display lower kinetic, but greater wrist spatial kinematic variability during daily propulsion compared to MWU without pain (Jayaraman et al., 2014; Moon et al, 2013; Rice et al., 2014). However, no studies have reported glenohumeral or scapulothoracic kinematic variability in either athletic or nonathletic populations.

Therefore, the purpose of this study was to determine kinetics, kinematics and kinematic variability during daily wheelchair propulsion on an ergometer and to establish if differences existed between athletic and nonathletic MWU. Success in this area may provide valuable information for future work in daily propulsion that can be applied to both athletic and nonathletic populations.

2. Methods

2.1. Participants

Thirty-nine full-time MWU (age = 36 ± 11 years; body mass = 75.9 ± 19.0 kg; years of MWU 18 ± 12 years) provided written informed consent to participate in the study. Ethical approval was obtained through the local ethical advisory committee. Participants were categorised as either athletes (n = 25) who regularly participated in wheelchair sports (basketball = 7, rugby = 9, tennis = 5, other = 4) or nonathletes (n = 14) who did not participate in any formal wheelchair sport activities. Participants in this study were part of an ongoing investigation into wheelchair propulsion and shoulder pain in manual wheelchair users. Study inclusion criteria required participants to be full-time wheelchair users, aged 18–55 years.

The prevalence of shoulder pain in each group was compared using the performance corrected Wheelchair User Shoulder Pain Index (PC-WUSPI) (Curtis et al., 1995; Curtis et al., 1999). A total PC-WUSPI score greater than zero indicated current shoulder pain. Athletic and nonathletic groups had a similar shoulder pain prevalence of 72% (18/25) and 71% (10/14), respectively.

2.2. Experimental protocol

Participants demographic information (age, body mass, sex, primary impairment and years as MWU) and wheelchair measurements (chair mass, wheel diameter, rim diameter and wheelbase) were collected. The Leisure Time Physical Activity Questionnaire for people with Spinal Cord Injury (LTPAQ-SCI) was used to quantify the duration of mild, moderate and heavy physical activity performed over the previous seven days (Martin Ginis and Latimer, 2007). All trials were performed on a dual roller wheelchair ergometer (Lode Esseda m988900, Groningen, Netherlands). After a five-minute warm up involving self-selected propulsion and dynamic stretching, participants performed two three-minute submaximal propulsion trials in their own daily chair at speeds that reflected daily propulsion (1.11 m s^{-1} and at 1.67 m s^{-1}) (Mason et al., 2014). Trials were performed in a counterbalanced order and separated by a two-minute rest period. Push phases were identified as the period where the ergometer roller torque trace exceeded 1 Nm (Goosey-Tolfrey et al., 2018; Vegter et al., 2013). Spatiotemporal and kinetic variables were calculated from the force and velocity data collected via the ergometer (Table 1).

2.3. Kinematics

A 10 camera (MX T40-S) Vicon motion analysis system (Vicon, Motion Systems Ltd. Oxford, United Kingdom) was used to capture upper limb kinematics during all trials at 200 Hz. Eighteen 14 mm retroreflective markers (B&L Engineering, California, USA) were attached to anatomical landmarks of both upper limbs and torso (Fig. 1) following International Society of Biomechanics (ISB) recommendations (Wu et al., 2005).

The acromion marker cluster (AMC) method, described in Warner et al. (2015), was used to establish the relative position of the acromial angle (AA), trigonum scapulae (TS) and inferior angle (AI) of both scapulae to the AMC (Fig. 1c) during a static trial. This known relationship was used to reconstruct the scapular landmarks during the motion trials (Warner et al., 2015). Glenohumeral joint centres (GHJC) were determined using the Symmetrical Centre of Rotation Estimation (SCoRE) method from a bilateral circumduction trial (Ehrig et al., 2006; Warner et al., 2015).

2.4. Kinematic analysis

Custom written MATLAB scripts (Matlab R2017a, The Mathworks Inc, Natickm MA, USA) were used for further data processing and analysis. A fourth-order, low-pass Butterworth filter was applied to marker trajectory data with a cut off frequency of 6-Hz (Morrow et al., 2011). Euler angles were determined for the scapulothoracic (scapula to thorax) and glenohumeral (humerus to scapula) joints following ISB recommendations (Wu et al., 2005). Glenohumeral rotations were described using rotation sequence ZXY as recommended to avoid singular positions and for tasks such as wheelchair propulsion where movement is primarily performed in the sagittal plane (Šenk and Cheze, 2006; Kontaxis et al., 2009; Schnorenberg et al, 2014; Slavens et al., 2015). Mean and standard deviations (inter-cycle variability) of time-normalised joint angles and joint centre displacements of the glenohumeral, elbow and wrist joints were extracted from 20 consecutive propulsion cycles of the final 60 s of each trial. Kinematic waveforms were offset-normalised using mean group and mean individual values to enhance statistical power (Mullineaux et al., 2004). At the end of each trial participants stopped and struck the top of the wheels, the peak vertical acceleration of the hand marker and the peak force were used to synchronise the motion capture system to the ergometer.

Table 1
Descriptions of spatiotemporal and kinetic characteristics following previously defined methods (Vegter et al, 2013; Mason et al, 2014).

Variable	Description
SF (push/min)	Number of pushes completed per minute
Push time (s)	The duration of hand push rim contact
Recovery time (s)	Duration of non push rim contact
Contact angle (°)	Wheel rotation angle during hand push rim contact
Peak torque (Nm)	Peak torque applied to ergometer roller
Relative mean power (W)	Torque multiplied by angular velocity divided combined body and chair mass
Work done per push (J)	Power integrated over the push time

Note: SF = Stroke frequency.

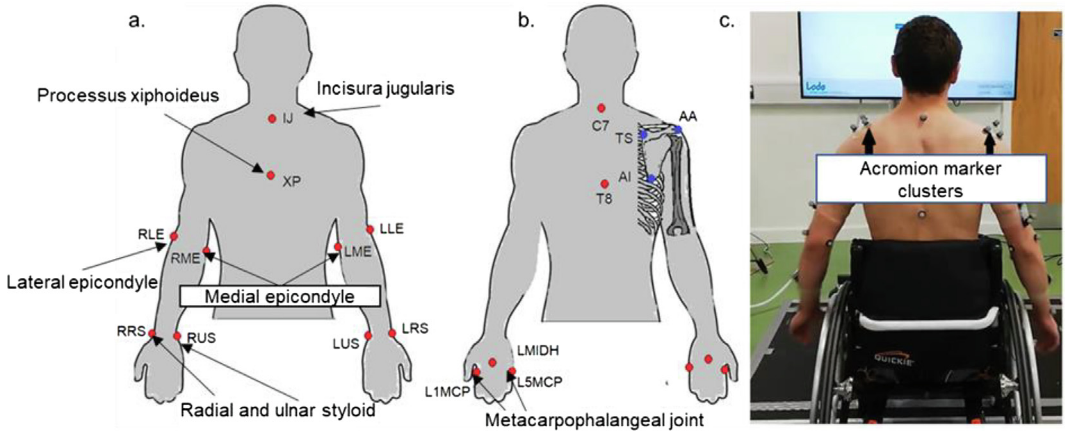

Fig. 1. Anatomical marker locations (anterior and posterior view). Scapula anatomical landmarks (1b), AA = acromial angle, TS = trigonum scapulae, AI = Inferior angle. Acromion marker clusters (1c).

2.5. Statistical analysis

A series of independent t-tests were performed in Statistical Package for Social Sciences (SPSS version 23, IBM, New York, USA) to investigate if significant differences existed between athletic and nonathletic MWU for personal, wheelchair and user-chair characteristics as well as spatiotemporal and kinetic variables from the motion trials. Corrected effect sizes (Cohen, 1988) for unequal samples were calculated and classified following previous recommendations as: trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2) and very large (>2) (Batterham & Hopkins, 2006). Kinematic waveforms were compared across the push phase and recovery phase separately using Statistical Parametric Mapping (SPM) two-tailed independent t-tests (α = 0.05) (Pataky et al., 2013). SPM analyses were conducted using open-source MATLAB code (SPM1d, v.M0.4.5, www.spm1d.org). Descriptions of SPM theory and methods are provided elsewhere (Friston et al., 2007; Pataky, 2012).

3. Results

Athletic MWU participated in a significantly greater number of minutes per week of moderate and heavy intensity physical activity compared to nonathletic MWU (Table 2). No significant differences in any personal or wheelchair characteristics were observed between athletic and nonathletic MWU (Table 2). During both speeds no significant kinetic or kinematic differences were observed between groups (Table 3, Fig. 2, Fig. 3). Subsequently data from the slowest speed only were presented, as this speed more closely represented daily propulsion (Figs. 2 and 3).

4. Discussion

The current study was the first detailed biomechanical comparison of athletic and nonathletic MWU propelling their daily wheelchair. Despite athletic MWU participating in significantly greater levels and intensities of physical activity per week, no significant differences in propulsion biomechanics were observed between athletic and nonathletic MWU. In addition, no differences in either personal, wheelchair characteristics or prevalence of shoulder pain existed between groups, which could have confounded the results. Therefore, these findings suggest that there is no distinction between how athletic and nonathletic MWU propel their daily wheelchairs.

Two notable kinematic features of daily propulsion were displayed by both populations. Firstly, all MWU displayed a

Table 2
Nonathletic and athletic personal, chair, and chair-user characteristics. ES = effect size.

Variable	Athletic (n = 25)	Nonathletic (n = 14)	P	ES	Meaning
Age (Yr)	35.2(10.9)	36.2(11.5)	0.79	0.09	Trivial
Years as MWU (Yr)	14.5(11.2)	17.4(12.4)	0.45	0.26	Small
Years of sports participation (Yr)	7(3.87)	NA			
LTPA (minutes per week)					
Mild	274.6(25 0)	239.4(132.4)	0.91	0.04	Trivial
Moderate*	358.6(364.3)	120(95.9)	0.009	0.95	Mod
Heavy*	286.8(248.1)	20.6(29.9)	0.001	1.2	Mod/large
Total*	920(601)	380(147)	0.001	0.92	Mod
Body mass (kg)	72.6(20)	79.9(13.9)	0.23	0.41	Small
Chair mass (kg)	12.2(1.44)	12.7(2.12)	0.4	0.3	Small
Rel. chair mass (%)	17.6(3.51)	16.2(3.89)	0.26	0.39	Small
Wheel diameter (m)	0.61(0.01)	0.61(0.01)	0.85	0	Trivial
Rim diameter (m)	0.55(0.01)	0.55(0.01)	0.49	0	Trivial
Wheelbase (m)	0.53(0.04)	0.54(0.05)	0.56	0.24	Small
GHJC position (Y)	0.03(0.05)	0.02(0.09)	0.68	0.11	Small
Mid hand position (Z)	0.13(0.04)	0.15(0.08)	0.43	0.36	Small
Elbow angle at TDC (°)	108(27.9)	113(28.9)	0.6	0.18	Small

Note: LTPA = Leisure time physical activity, GHJC = glenohumeral joint centre relative to wheel axel, Mid hand position relative to wheel axel, TDC = top dead centre of push rim.

Table 3
Spatiotemporal and kinetic characteristics of the nonathletic and athletic groups during daily propulsion. ES = effect size.

Variable	Athletic (n = 25) 1.11 m.s^{-1}	Nonathletic (n = 14)	P	ES	Meaning	Athletic (n = 25) 1.67 m.s^{-1}	Nonathletic (n = 14)	P	ES	Meaning
SF (Push/min)	52(10)	55(15)	0.43	0.25	Small	62(15)	68(31)	0.42	0.29	Small
Push time (s)	0.38(0.08)	0.35(0.06)	0.19	0.41	Small	0.26(0.07)	0.25(0.05)	0.43	0.16	Trivial
Rec time (s)	0.75(0.16)	0.77(0.16)	0.67	0.13	Trivial	0.78(0.28)	0.78(0.33)	0.78	0	Trivial
Contact angle (°)	84.2(13.9)	79.6(13.9)	0.33	0.34	Small	86.9(12.7)	83.1(15.5)	0.41	0.28	Small
Peak Torque (Nm)	13.9(3.6)	15.4(7.3)	0.39	0.3	Small	16.8(3.9)	16.8(6.8)	0.98	0	Trivial
Rel. Power Output (W/kg)	0.2(0.05)	0.2(0.08)	0.92	0.09	Trivial	0.35(0.1)	0.31(0.12)	0.23	0.38	Small
Work per push (J)	13(6)	14(4)	0.46	0.19	Small	16(5)	15(6)	0.48	0.18	Trivial

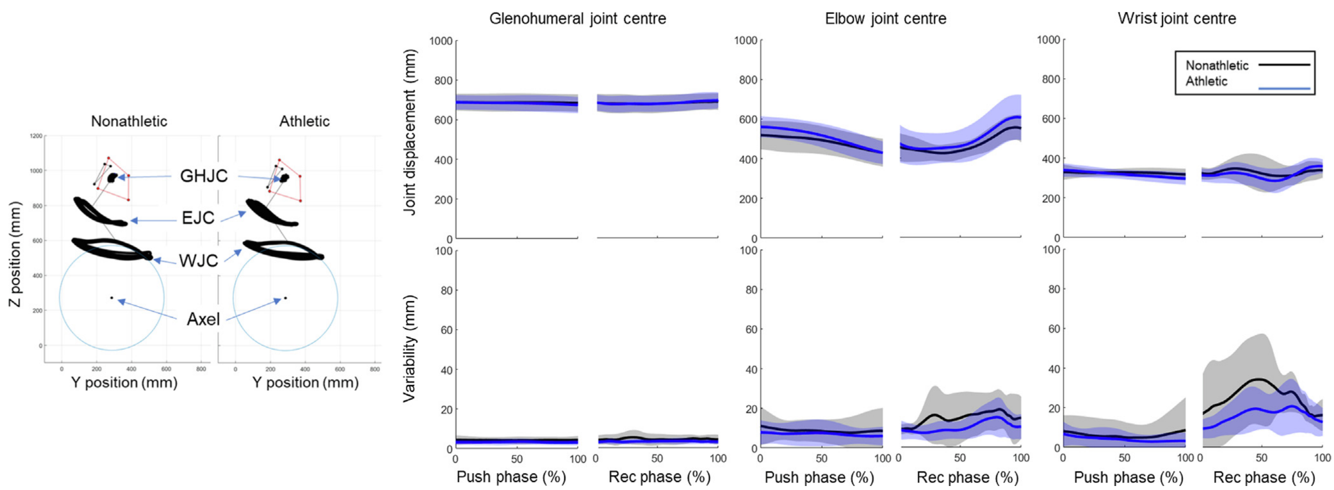

Fig. 2. Comparison of group mean joint displacements relative to the wheel axel and joint spatial variability of the glenohumeral joint centre (GHJC), elbow (EJC) and wrist (WJC) of the nonathletic (black) and athletic (blue) groups during the slowest speed. SPM1d independent t-tests found no significant joint displacement or joint spatial variability between the groups at either propulsion speed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

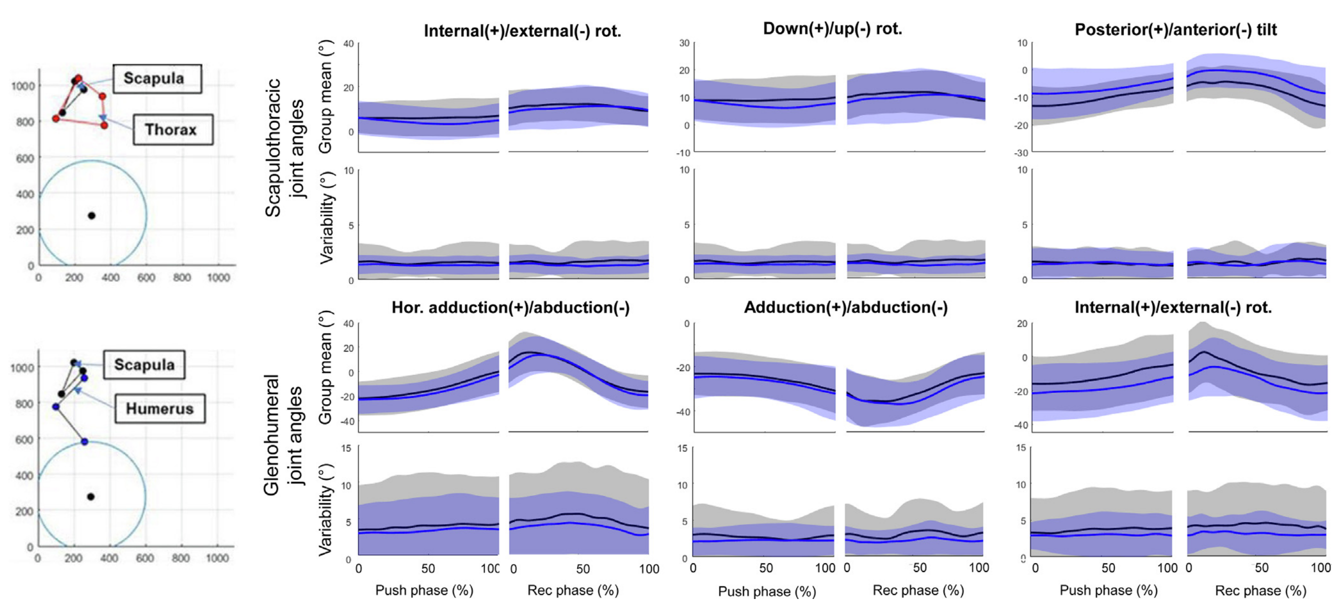

Fig. 3. Comparison of group mean joint kinematics and joint kinematic variability of the scapulothoracic and glenohumeral joint of the nonathletic (black) and athletic (blue) groups during the slowest speed. SPM1d independent t-tests found no significant joint kinematic or kinematic variability differences between the groups at either propulsion speed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concomitant presence of peak internal rotation and downward rotation of the scapula and greatest internal rotation of the glenohumeral joint during the early part of the recovery phase. This trend has also been observed in previous nonathletic studies (Morrow et al., 2011; Raina et al., 2012; Zhao et al., 2015) and the single previous athletic study (Mason et al., 2018). As these kinematic characteristics are most closely associated with shoulder pain development, investigations should explore this region of the propulsion cycle in future shoulder pain research (Morrow et al., 2011). Secondly, while wrist joint variability is greater during the recovery phase all other joint spatial and joint angle variability parameters remained relatively consistent throughout both push and recovery phases. Previous, shoulder pain investigations of joint spatial kinematic variability during daily propulsion have only explored the recovery phase (Jayaraman et al., 2014). However, the present study suggests that movement variability of proximally located joint structures are not as constrained by push rim contact. Thus, future work should explore the association between shoulder pain and variability in proximal joints during the push and recovery phases.

The current findings have additional implications for research and applied practice. This work suggests that research findings and guidelines directed towards daily propulsion in nonathletic populations may be viewed as relevant to clinicians and sports medicine professionals working with wheelchair athletes (Boninger et al., 2002; Sawatzky et al., 2015). In addition, future work investigating shoulder pain risk factors associated with daily propulsion do not need to distinguish between athletic and nonathletic populations.

5. Study limitations

Comparing populations using prescribed submaximal speeds may have constrained any spatiotemporal or kinetic group differences that may be present during self-selected speeds. However, the absence of any significant joint kinematic differences between populations suggests the interpretation that athletic and nonathletic do not propel their daily wheelchair differently is valid. Additionally, an assumption of this work was that due to greater physical activity levels the athletic MWU will possess greater strength and physical capacity as shown previously (Freitas et al., 2019). However, no comparison of strength measures or muscle activity was undertaken. Thus, no comment can be made on the relative demand daily propulsion places on each population. One further limitation is that propulsion was performed on a roller ergometer rather than over-ground. Previous studies report biomechanical differences such as work per cycle and peak forces between ergometer and over-ground propulsion (Koontz et al., 2012; Mason et al, 2014) which may limit the relevance of these findings to over-ground propulsion.

6. Conclusions

Despite differences in physical activity, there is no distinction between kinetic or kinematic parameters of how athletic and nonathletic MWU propel their daily wheelchair. These findings suggest that athletic and nonathletic MWU can be viewed in a similar manner when investigating the association between shoulder pain and daily propulsion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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