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Propulsion kinetics of recumbent handcycling during high and moderate intensity exercise

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ABSTRACT

People with spinal cord injuries (PwSCI) are at high risk of developing cardiovascular disease (CVD). While regular exercise can reduce risk of CVD, PwSCI face various barriers to exercise, including high rates of upper limb injuries, especially in the shoulder. Handcycling high intensity interval training (HIIT), which consists of periods of high intensity exercise followed by rest, is a potential exercise solution, but the musculoskeletal safety of HIIT is still unknown. In this study, we characterized three-dimensional continuous applied forces at the handle during handcycling HIIT and moderate intensity continuous training (MICT). These applied forces can give an early indication of joint loading, and therefore injury risk, at the shoulder. In all three directions (tangential, radial, and lateral), the maximum applied forces during HIIT were larger than those in MICT at all timepoints, which may indicate higher contact forces and loads on the shoulder during HIIT compared to MICT. The tangential and radial forces peaked twice in a propulsion cycle, while the lateral forces peaked once. Throughout the exercises, the location of tangential peak 2 and radial peak 1 was later in HIIT compared to MICT. This difference in maximum force location could indicate either altered kinematics or muscular fatigue at the end of the exercise protocol. These changes in kinematics should be more closely examined using motion capture or other modeling techniques. If we combine this kinetic data with kinematic data during propulsion, we can create musculoskeletal models that more accurately predict contact forces and injury risk during handcycling HIIT in PwSCI.

1. Introduction

There are approximately 300,000 people living with spinal cord injuries (SCIs) in the United States, with 18,000 new cases of SCI each year, most commonly caused by car accidents and falls (National Spinal Cord Injury Statistical Center, 2021). People with spinal cord injuries (PwSCI) face a number of secondary complications as a result of their injury (National Spinal Cord Injury Statistical Center, 2021), including high rates of cardiovascular disease (CVD) (Washburn et al., 2002; Martin Ginis et al., 2010; Tanhoffer et al., 2014; Blair, 2009; Thyfault and Krogh-Madsen, 2011). CVD is prevalent at an earlier age (Whiteneck et al., 1992; Bauman et al., 1999) and is the number one cause of premature deaths in PwSCI (Garshick et al., 2005). While CVD risk can be reduced through regular exercise (Nash, 2005; Blair et al., 1996; Grundy et al., 2005; Green et al., 2008), numerous barriers impede the likelihood for PwSCI to engage in exercise (Washburn et al., 2002; Dearwater et al., 1986; Martin Ginis et al., 2010). Additionally, current exercise guidelines for this population are not effective at reducing CVD risk (Totosy de Zepetnek et al., 2015; Nightingale et al., 2017; Tanhoffer et al., 2014), highlighting a need to develop new exercise programs specific to PwSCI that improve CV health in this population.

A secondary complication for PwSCI is musculoskeletal soft tissue injuries and shoulder pain (Curtis et al., 1999; Bayley et al., 1987; Pentland and Twomey, 1994; Waring and Maynard, 1991), which are prevalent in up to 72% of wheelchair users (Subbarao et al., 1995). The repeated loading patterns from wheelchair propulsion can lead to overuse injuries in the shoulder (Barber and Gall, 1991) including rotator cuff impingement (Bayley et al., 1987), tendinopathy (Jahanian et al., 2020; Gill et al., 2014), and degenerative soft tissue morphological changes (Brose et al., 2008). Thus, any new exercise guidelines for PwSCI should not only be evaluated for their effectiveness at improving CV health but also for their musculoskeletal safety.

High intensity interval training (HIIT), which involves intervals of high intensity exercise periods and active rest periods, is an alternative exercise solution to the traditional moderate intensity continuous

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training (MICT). HIIT reduces CVD risk in both able-bodied (Su et al., 2019) and SCI populations (Harnish et al., 2017; Hooker and Wells, 1989; Devillard et al., 2007). Additionally, the frequent rest periods in HIIT may help overcome early onset muscle fatigue (Nightingale et al., 2017; Nash, 2005) making it more optimal for PwSCI than traditional modes of continuous exercise (Heyward et al., 2017).

While the impact of HIIT on CV health has been investigated, the impact of HIIT on shoulder health in PwSCI is still unknown. One potential way to reduce injury risk during HIIT is to exercise on a handcycle compared to a traditional wheelchair. Handcycling involves synchronous crank propulsion that uses a gear system attached to the crank and wheels. Compared to everyday wheelchair propulsion, handcycling is more physiologically efficient (Dallmeijer et al., 2004) and results in smaller shoulder loads and contact forces (Arnet, 2012). Therefore, handcycling may be a helpful alternative to everyday wheelchair propulsion, especially during HIIT which features higher speeds and intensities.

Although HIIT has been associated with more self-reported upper body discomfort and shoulder pain in PwSCI (Schoenmakers et al., 2016; Gauthier et al., 2018), a more robust investigation of the underlying shoulder mechanics during handcycling HIIT is still needed because many rotator cuff injuries are asymptomatic (Gill et al., 2014; Minagawa et al., 2013) and cannot be diagnosed from self-reported surveys alone. The first step in examining the shoulder mechanics during handcycling is to quantify the applied forces at the handcycle handle. Shoulder loads are a function of muscle and joint contact forces — which are dependent, in part, on the applied forces at the handle. Therefore, the handle reaction force can provide insight into shoulder kinetics during handcycling and give a preliminary indication of injury risk during exercise.

To our knowledge, four studies have reported continuous applied forces at the crank during attach-unit handcycling (Van Drongelen et al., 2011; Arnet et al., 2013; Kraaijenbrink et al., 2017, 2020). One study has directly measured applied forces during recumbent handcycling (Jakobsen and Ahlers, 2016), with other studies measuring torque (Mason et al., 2021; Vegter et al., 2019; Quittmann et al., 2018, 2020). However, no studies have reported three-dimensional applied forces during recumbent handcycling. Thus, the purpose of this study was to characterize the kinetic profiles of recumbent handcycling during HIIT and MICT. We measured three-dimensional applied forces at the crank handle during recumbent handcycling in HIIT and MICT in wheelchair users. Using this data, we analyzed the location of maximum tangential, radial, and lateral forces to determine locations of interest. We hypothesized that the higher speeds and power outputs during HIIT would result in higher applied forces compared to the traditional mode of exercise, MICT. We also hypothesized that the prolonged exercise in MICT would result in a degradation of propulsion technique in MICT compared to HIIT. Because tangential forces are the only forces directly contributing to propulsion, this degradation would be characterized by a decrease in tangential forces and increase in radial and lateral forces compared to no change in propulsion technique in HIIT.

2. Methods

This study was approved by the Institutional Review Board at the University of Illinois. All testing was performed at the Wheelchair Biomechanics Lab.

2.1. Participants

Twenty-one participants were recruited from the University of Illinois adapted sports teams. Participants were pre-screened using the American College of Sports Medicine (ACSM) Pre-Participation Screening Algorithm, which includes a series of questions to ensure that participants are regularly active and do not have or exhibit symptoms of cardiovascular, metabolic, or renal disease. If these conditions are met, participants do not need medical clearance for vigorous intensity exercise according to ACSM guidelines (Riebe et al., 2015). Inclusion criteria were (1) age 18–45, (2) at least 12 months post onset of neurologically stable spinal cord injury or spinal cord dysfunction, (3) participation in vigorous intensity exercise in the last 30 days, and (4) met the American College of Sports Medicine (ASCM) minimum physical activity recommendations (150 min of moderate intensity exercise and 2 days of strengthening activities per week) (ACSM, American College of Sports Medicine, 2017). If individuals exhibited signs or symptoms of CVD, regular upper extremity pain, or other conditions or injuries preventing them from safely participating in sports activities, they were excluded from the study. Participants signed an informed consent form and completed a demographic survey where sex, age, height, weight, and years with disability data was recorded.

Table 1
Exercise protocols completed by participants. Abbreviations: HIIT (High intensity interval training), MICT (Moderate intensity continuous training), PO (power output), PPO (peak power output).

Session	Protocol	PO
1	Incremental test to exhaustion	30 W, increase by 10 W every minute
2	High intensity interval training	1 min at 90% PPO 1 min at 10% PPO 10 total intervals
3	Moderate intensity continuous training	45% PPO

2.2. Exercise protocols

Prior to each session, participants were asked to refrain from strenuous exercise, caffeine, and alcohol for 24 h (ACSM, American College of Sports Medicine, 2017). All exercises were completed on a recumbent handcycle (Top End, Invacare, USA). To maintain a common seating configuration among participants, the handcycle was adjusted such that at the maximal reach phase the elbows were flexed between 15 and 20°, which has been shown to maximize power production (Mossberg et al., 1999).

Participants completed three exercise sessions (Table 1) 2–10 days apart (average: 4.2 ± 2.3 days) beginning with an incremental test to exhaustion (Schoenmakers et al., 2016) wherein participants began cycling at 30 W after which power was increased by 10 W every minute until they voluntarily stopped cycling or were no longer able to maintain the selected power output. Power output was collected at 2 Hz using a powermeter (SRM, Julich, Germany) attached to the handcycle hub. Each participant's peak power output (PPO) was calculated as:

$$PPO = P_{max} + (t * 10W) \tag{1}$$

where P_{max} was the final PO the participant was able to complete for 60 s and t was the time (in minutes) that participants cycled into the next interval before stopping. After the incremental test, participants remained on the handcycle for 8–10 minutes to recover, either by handcycling slowly or resting. Once participants were recovered, they completed a HIIT familiarization routine, which involved one interval of the HIIT protocol (Table 1) (Astorino and Thum, 2016; Currie et al., 2013).

The second exercise session was a HIIT session which consisted of 10 intervals of high and low-intensity exercise. For each interval, participants cycled for one minute at 90% PPO, followed by one minute at 10% PPO (Currie et al., 2013; Little et al., 2011).

The third session, MICT, involved participants cycling at 45% PPO (Jacobs et al., 2013) until the work done during MICT matched the work completed during HIIT. Total work, W_{total}, was calculated by

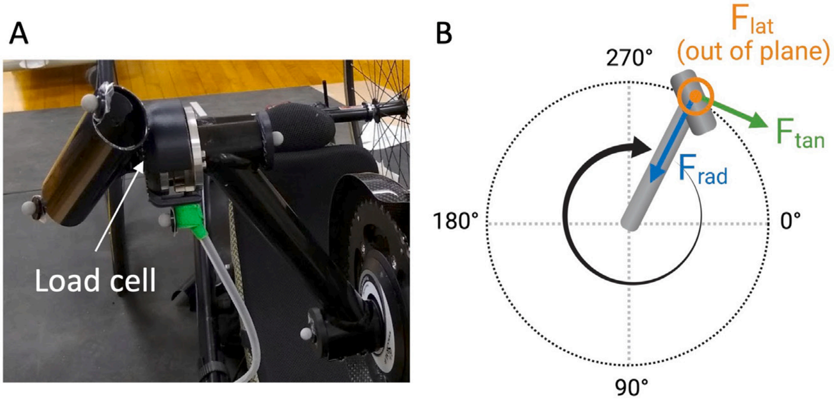

Fig. 1. (A) Handcycle handle instrumented with the six-axis load cell and with 5 markers attached to track crank angle and handle movement. (B) Handcycle angle and force conventions used in this paper, with the 0° position being the furthest away from the body. F_{tan} is positive when pointing in the direction of rotation, positive F_{rad} is radially inward, and positive F_{lat} is pointing in the lateral direction (away from the participant).

integrating the power–time curve using a trapezoidal sum in MATLAB (Mathworks, Natick, USA) from which the time for the MICT session (t_{MICT}) was calculated as:

$$t_{MICT} = W_{total}/(0.45 * PPO) \tag{2}$$

where *PPO* was the participant's peak power output, calculated in Eq. (1).

After both the HIIT and MICT sessions, participants were given 5–10 minutes in the handcycle to recover before leaving the testing site.

2.3. Hand crank kinetics

Applied forces at the right hand crank were collected during both the HIIT and MICT sessions at 2000 Hz using a custom handle instrumented with a six-axis load cell (ATI, Apex, USA). The resolution of the load cell was 0.25 N for force measurements and 0.005 Nm for torque measurements, with an estimated error between 1.00% and 1.75%. Bilateral symmetry was assumed which is consistent with previous literature (Van Drongelen et al., 2011; Kraaijenbrink et al., 2017, 2020). The angle of the crank and handle were measured using five reflective markers (Fig. 1A). Marker motion was recorded at 100 Hz using a 10-camera Vicon Nexus motion capture system (Vicon Motion Systems, Yarnton, UK).

Synchronous force and crank/handle motion data were collected during the 1st, 3rd, 5th, 7th, 9th, and 10th HIIT high intensity (90% PPO) intervals. Similarly, data was collected at 6 timepoints during the MICT session that matched the workloads at the 6 HIIT collection timepoints.

2.4. Rate of perceived exertion (RPE)

Rate of Perceived Exertion (RPE) was collected at each of the six workload-matched timepoints in HIIT and MICT using a Borg scale (Borg, 1998; Ritchie, 2012) ranging from 6–20, where 6 was no exertion and 20 was maximal exertion.

2.5. Data analysis

Data processing was completed in MATLAB. Kinetic data was filtered using a 2nd order low-pass Butterworth filter with a cutoff frequency of 10 Hz. We identified the first ten propulsion cycles at each timepoint using the recorded motion data, denoting 0° as the most distal (furthest away from the user) crank position. The local load cell x, y, and z-coordinate system was converted to the tangential (F_{tan}), radial (F_{rad}), and lateral (F_{lat}) handcycle coordinate system using the marker positional data (Fig. 1B). The force profiles were averaged over the 10 propulsion cycles to obtain a representative force profile for each participant at each exercise and timepoint. We measured the maximum force magnitude in the tangential, radial, and lateral directions and the corresponding location of maximum force during the rotational cycle for each participant at each timepoint. The tangential force and radial force profiles consisted of 2 peaks and the relative magnitude of these peaks varied between participants. Therefore, to avoid comparing the maximum peaks at two different locations, both tangential peaks and both radial peaks were identified as locations of interest during the propulsion cycle. Lastly, the impulse applied by participants was calculated by integrating the resultant force, defined as the magnitude of the total applied force, over time.

2.6. Statistical analysis

Statistical analysis was completed in RStudio (Boston, USA). Variables were tested for normality using a Shapiro–Wilk test. Because some variables were not normally distributed, a Wilcoxon signed-ranks test ($\alpha = 0.05$) was used to compare the maximum forces, maximum force locations, RPE, and impulse values between HIIT and MICT at the same timepoint and between timepoint 1 and timepoints 2–6 within the same exercise test.

3. Results

3.1. Participants

Twenty-one participants were recruited (Table 2). One person dropped out after Session 1 (incremental test) due to health reasons unrelated to the study and their data was excluded. Twenty participants completed all exercise tests, with an average of 4.2 ± 2.3 days between exercise protocols. Whenever possible, protocols were completed at the same time of day for each subject, resulting in an average difference of less than one hour (0.97 ± 1.2 h) between exercise start times for each subject. No adverse events or injuries were recorded during or after exercise testing.

Participants all had either a spinal cord injury (L1 n = 1, T11 n = 2, T10 n = 2, T9 n = 2, T3 n = 1), or spinal cord dysfunction (spina bifida n=8, transverse myelitis n=3, and cauda equina syndrome n=1). All participants used wheelchairs as their main mode of transportation.

3.2. Rate of perceived exertion

Rate of perceived exertion (RPE) data was successfully recorded for seventeen participants (three datasets were unrecoverable). HIIT RPE was higher than MICT at every timepoint ($p = 0.0003$–0.002, Table 3).

Table 2
Participant demographics. Data are mean±SD.

n	Sex	Age (years)	BMI	Years living with disability	PPO (W)	Mass (kg)	Power to Mass Ratio (W/kg)
20	9 f, 11 m	25.50±6.83	23.52±4.81	19.85±5.75	136.33±36.67	63.43±14.43	2.26±0.57

Table 3
RPE scores (Borg scale) for participants (n=17) and Impulse (N*s) of resultant force during propulsion (n=20). Data are median (median absolute deviation). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ comparing MICT to HIIT.

Timepoint	1	2	3	4	5	6
RPE (Borg)						
MICT	7 (0.0)	8 (1.5)	11 (3.0)	11 (3.0)	12 (3.0)	12 (3.0)
HIIT	9 (3.0)**	12 (3.0)***	13 (3.0)***	14 (1.5)***	16 (3.0)***	16 (3.0)***
Impulse (N*s)						
MICT	33.1 (9.0)	31.7 (7.4)	31.9 (9.0)	32.6 (10.3)	32.5 (8.8)	31.9 (6.3)
HIIT	35.1 (6.1)***	34.1 (6.2)***	35.2 (8.5)***	35.0 (5.6)***	37.0 (8.5)***	37.6 (9.4)***

Table 4
Maximum force component magnitudes at each timepoint for each exercise protocol. Data are median (median absolute deviation). * denotes significantly different distributions from MICT timepoint, where *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. ^{a} indicates significantly different distributions from timepoint 1 of the same exercise protocol, where ^{a} is $p < 0.05$.

	Timepoint					
	1	2	3	4	5	6
F_{tan} (N)						
MICT	48.2 (11.3)	49.0 (12.9)	50.8 (14.8)	52.7 (18.2)	52.8 (16.1)	54.7 (15.6)
HIIT	83.7 (34.5)***	82.7 (29.5)***	76.2 (23.7)***	77.6 (25.5)***	79.7 (19.8)***	81.1 (17.1)***
F_{rad} (N)						
MICT	31.4 (10.8)	30.8 (6.8)	30.6 (8.2)	29.4 (5.9)	32.4 (8.2)	32.6 (9.5)
HIIT	38.8 (14.3)*	39.3 (10.2)**	42.8 (14.2)**	43.9 (10.3)***	42.3 (8.2)***	45.7 (17.7)***
F_{lat} (N)						
MICT	8.8 (2.7)	10.3 (4.5)	10.0 (5.4)^a	9.7 (3.8)	10.5 (4.5)	9.6 (5.2)
HIIT	15.9 (6.5)***	17.4 (7.0)***	16.1 (5.9)***	16.1 (6.0)***	15.6 (8.8)***	16.9 (7.5)***

3.3. Maximum force magnitudes

Due to a malfunction with the load cell during testing, force data from timepoint 3 of participant 18's MICT protocol was excluded as well as the corresponding HIIT data.

The maximum tangential, radial, and lateral forces for each participant at each timepoint were calculated during HIIT and MICT to analyze the differences in the distribution of force magnitudes. During both exercise protocols, tangential forces were the largest followed by radial and then lateral (Fig. 2 A–C). For all three force components, HIIT forces were significantly different than those of MICT forces at every timepoint. The maximum tangential forces during HIIT were 54.2% higher than MICT forces ($p < 0.001$, Table 4). Similarly, the maximum radial forces were 38.0% higher in HIIT than MICT (p-range = 0.001–0.05). While lower in magnitude, the maximum lateral forces were 63.9% higher in HIIT compared to MICT ($p < 0.001$).

There were no significant differences in maximum forces from timepoint 1 through the rest of the protocol. The sole exception occurred in the maximum lateral forces during MICT which differed between timepoint 1 and timepoint 3 ($p = 0.014$) by 1.2 N. The amount of maximum force generated during handcycling was correlated to the peak power output based on the prescribed power levels for both HIIT and MICT (Fig. 2 D, E, and F). The amount of variation in maximum force that could be explained by peak power output was higher in HIIT (R^2 range = 0.35–0.55, $p < 0.001$) compared to MICT (R^2 range = 0.052 to 0.37, $p < 0.01$).

The impulse applied by participants during a propulsion cycle was higher in HIIT compared to MICT (32.0 N*s compared to 35.3 N*s, 10.3% increase, Table 3). This difference was significant across all timepoints ($p < 0.001$). No difference was found between impulses in timepoint 1 of an exercise protocol and subsequent timepoints of the same exercise protocol.

3.4. Maximum force locations

There were two peaks in tangential force profiles during handcycling reflective of the pull phase (first peak) and push phase (second peak) (Fig. 3A). The tangential forces were positive during the propulsion cycle. There was no difference in the location of the first peak of the tangential forces during HIIT (average = 57.0°) compared to MICT (average = 53.5°) and peak location did not change during the course of exercise (Table 5, p-range = 0.07–0.96). Similarly, the location of the second tangential peak was not significantly different between HIIT and MICT with the exception of timepoint six which had a shift of 6° ($p = 0.029$, Table 5). Overall, there were no significant differences during the course of exercise for either peak except for a 1° shift in MICT peak 2 between timepoints 1 and 2.

The radial forces were both positive and negative during a single propulsion cycle and were described by multiple peaks with a maximum radial force at 337.5–360.0° and a minimum radial force at 103.5–112.0° (Fig. 3B) during both HIIT and MICT, which correspond to push towards the crank axis and away from the crank axis, respectively. The maximum radial force (noted as Peak 1) occurred at 340° in MICT and 349.0° in HIIT (Fig. 3E). The maximum radial force during timepoint six occurred 16° later in HIIT compared to MICT ($p = 0.04$, Table 5). The minimum radial force (Peak 2) occurred on average at 106.0° in MICT and 108.0° in HIIT with a 4.5° shift in HIIT compared to MICT at timepoint 4 ($p = 0.02$). There was no difference in radial force locations during the course of exercise for either MICT or HIIT.

The lateral force magnitude tended to have one peak (Fig. 3C). While not significantly different, HIIT lateral forces peaked 8.3% earlier in the propulsion cycle than MICT lateral forces (Table 5). Similarly, there were no differences between HIIT and MICT lateral forces within timepoints or between timepoint 1 and future timepoints (Fig. 3F).

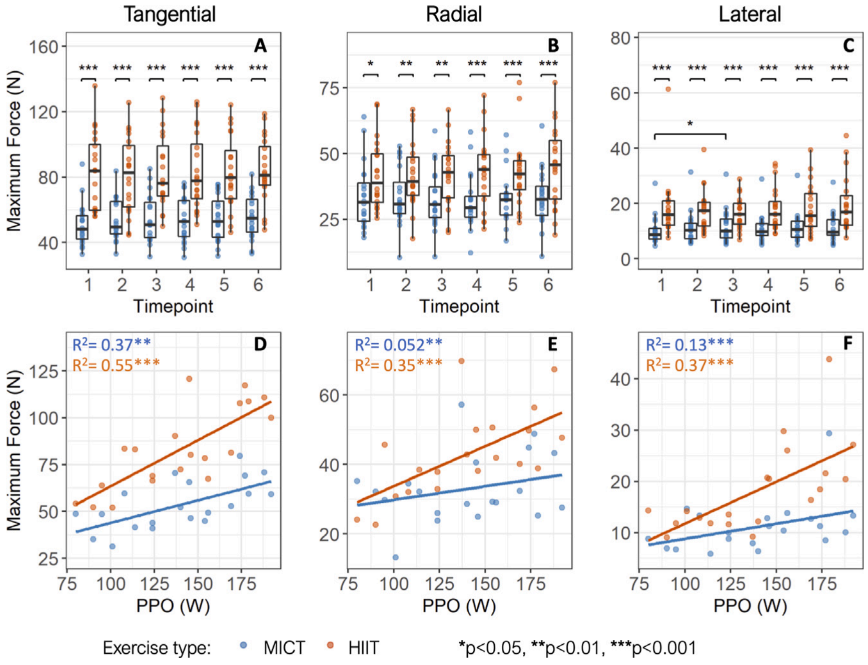

Fig. 2. Maximum forces in a propulsion cycle. Values of maximum tangential forces (left column), radial forces (center column) and lateral forces (right column) are plotted on the top row (graphs A, B, and C). The relationship between the average maximum forces for each participant compared to their peak power output (PPO) are plotted on the bottom row (graphs D, E, and F). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 5
Peak force locations at each timepoint for each exercise protocol. Data are median (median absolute deviation). The median column is the median peak force location across all subjects. * denotes significantly different distributions from MICT timepoint, where *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. ^{a} indicates significantly different distributions from timepoint 1 of the same exercise protocol, where ^{a} is $p < 0.05$.

		Timepoint						
		1	2	3	4	5	6	Median
Ftan (°)								
Peak 1	MICT	53.5 (11.9)	54.5 (19.3)	52.5 (14.8)	55.0 (16.3)	51.5 (17.8)	51.5 (16.3)	52.0 (14.5)
	HIIT	58.5 (19.3)	56.5 (14.8)	54.0 (13.3)	57.5 (14.1)	59.0 (13.3)	56.5 (20.0)	57.8 (13.7)
Peak 2	MICT	220.0 (17.8)	**219.0 (20.8)**^{a}	219.5 (16.3)	219.0 (14.1)	219.5 (16.3)	217.0 (14.8)	222.0 (17.4)
	HIIT	220.0 (8.9)	224.5 (8.2)	224.0 (10.4)	225.0 (12.6)	222.5 (11.9)	**223.0 (13.3)***	223.3 (8.15)
Frad (°)								
Peak 1	MICT	337.5 (17.8)	340.0 (16.3)	339.5 (11.9)	340.5 (13.3)	337.5 (17.0)	344.0 (22.2)	341.5 (16.3)
	HIIT	353.0 (44.5)	341.0 (28.9)	351.0 (43.0)	343.5 (24.5)	350.0 (36.3)	**360.0 (32.6)***	348.3 (28.9)
Peak 2	MICT	108.0 (20.0)	107.0 (19.3)	106.5 (16.3)	105.0 (13.3)	104.5 (16.3)	103.5 (14.1)	105.3 (17.8)
	HIIT	111.5 (34.1)	108.5 (21.5)	108.0 (17.8)	**109.5 (14.1)***	107.0 (17.0)	112.0 (22.2)	107.0 (18.2)
Flat (°)								
Peak 1	MICT	165.0 (91.2)	149.5 (97.1)	167.0 (112.7)	141.0 (57.8)	142.5 (61.5)	152.0 (74.1)	143.8 (75.6)
	HIIT	145.5 (99.3)	141.0 (57.8)	139.0 (84.5)	146.0 (68.2)	148.0 (78.6)	128.5 (32.6)	141.0 (81.9)

4. Discussion

Overall, the maximum applied forces were larger in HIIT compared to MICT. There were changes in the location of these maximum forces in HIIT compared to MICT towards the end of the protocols. There was very little change in the value and location of the maximum forces in timepoint 1 compared to subsequent timepoints within HIIT or MICT.

4.1. *Maximum force magnitudes*

We observed a large amount of inter-participant variation in the maximum forces at each timepoint, likely due to the design of our exercise protocol which used a participant-specific intensity level for peak power output (PPO). The target power output during HIIT and MICT was a significant correlate of the maximum forces reached during a propulsion cycle and more so during HIIT compared to MICT for all force components (Fig. 2 D–F).

Despite this variation, the tangential component was consistently the largest of the three components in agreement with data from others (Van Drongelen et al., 2011). Importantly, all participants were able to complete the exercise protocol. There was no change in the maximum forces between timepoint 1 and timepoints 2–6 except for the lateral forces in MICT timepoint 3. Participants maintained the same force output during both the HIIT and MICT protocols suggesting that neither protocol results in musculoskeletal fatigue to the point where participants could no longer maintain their intended power output. Additionally, the general lack of differences in maximum forces between the first timepoint and subsequent timepoints within an exercise protocol suggests that there was little to no degradation of propulsion technique during MICT or HIIT, which was contrary to our hypothesis that the lack of rest periods during MICT would result in changes in propulsion technique. The consistency in propulsion technique during both MICT and HIIT could indicate that participants were not fatigued during either protocol. These results are promising for HIIT to serve

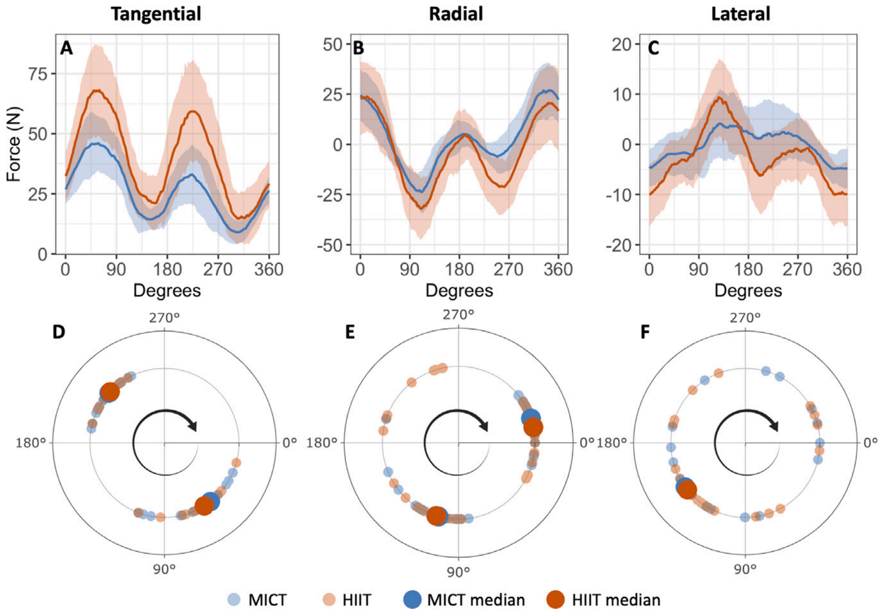

Fig. 3. Median profiles and median absolute deviation (shaded) for (A) tangential force, (B) radial force, and (C) lateral force for HIIT and MICT. Median location of points of interest for (D) tangential, (E) radial, and (F) lateral forces during both HIIT and MICT protocols. Peak force location for each subject (median over all timepoints) is shown by the smaller shaded dots. The median location across all subjects is indicated with a larger dot.

as a potential exercise for challenging the cardiovascular system in a sustainable manner.

While the radial and lateral force components during handcycling do not contribute to forward motion, they are unavoidable forces during handcycling. We found that the radial forces were nearly half as large as the tangential forces. From a training perspective, it would be desirable to eliminate or minimize this radial force because it does not contribute to forward propulsion. However, it is unclear how this applied force at the handle translates to and affects shoulder contact forces and joint moments. Bregman and colleagues suggested that the non-tangential forces are important in reducing the glenohumeral contact forces in everyday wheelchair propulsion (Bregman et al., 2009) based on their finding that applying 100% tangential forces increases shoulder moments (Bregman et al., 2009). However, wheelchair propulsion techniques and biomechanics differ considerably from handcycling where the individual is continuously applying forces throughout the 360° cycle. Differences in applied force magnitude, direction, and shoulder moment arm between handcycling and wheelchair propulsion result in different shoulder moments (Arnet et al., 2013). It is still unknown whether the non-tangential forces should be minimized in handcycling to increase force effectiveness, or if they should be encouraged to lower joint moments and therefore shoulder injury risk.

In comparing HIIT to MICT, it was clear that HIIT required larger forces. The tangential forces were almost double in HIIT versus MICT and it is therefore likely that handcycling during HIIT results in larger forces within the shoulder compared to MICT, though for a shorter duration. Similarly, the maximum resultant forces were 51.3% higher in HIIT compared to MICT (53.5 N compared to 81.0 N). Impulse, a measure of resultant force applied over time, was 10.3% higher in HIIT compared to MICT; however whether the increased applied impulse during HIIT negatively affects the shoulder remains to be confirmed and is the subject of future work. Importantly, no subjects reported pain and all were able to complete both the HIIT and MICT protocols. Whether or not a longitudinal exercise protocol involving HIIT would result in musculoskeletal injury is unknown. However, we believe the use of a participant-specific targeted power output level is one mechanism for mitigating the potential for overuse injuries during exercise, as the use of a target PO relative to each participants' maximum PO allows all participants to exercise at similar intensities.

4.2. Maximum force locations

The location of maximum tangential and radial forces during handcycling was different at the end of exercise when comparing HIIT to MICT. Temporal changes in kinetics could indicate differences in kinematics due to muscular fatigue. The RPE values during HIIT increased more than MICT. However, while RPE can give an indication of subjective fatigue, the level of musculoskeletal fatigue that may result in altered force application at the end of the protocols remains to be confirmed. The maximum positive radial force, which corresponds to the participant pulling the most towards the center of the crank, occurred between 340–349° for both HIIT and MICT. At this location the arm is almost fully extended in the handcycle and could be a potential point for investigation. In the case of handcycling, this location will result in a maximum moment arm of the applied forces exerted on the handle about the shoulder and could place the shoulder at increased risk for injury. While the kinematics of handcycling are limited due to the prescribed nature of handcycling motion and the fact that the hand is in contact with the handcycle at all times, changes in elbow movement are still possible and could influence force direction and shoulder moments. The potential differences in kinematics and muscle force application should be investigated further using motion capture or inverse dynamics techniques. Understanding how propulsion style changes throughout the exercise protocol can give a better understanding of ways to improve propulsion, inform seating and body position, or reduce injury risk.

There were several outliers in radial force patterns that resulted in two groups of peak radial forces: one at 200° and another at 250° (Fig S1). When these 60 data points were removed, there was a significant ($p < 0.05$) difference in the first peak radial force location from MICT to HIIT in timepoint 1, 5, and 6 ($p = 0.03$, 0.008, and 0.01, respectively). There was no significant difference in the distribution of the location of radial peak 2 in HIIT compared to MICT with the extraneous points removed. Interestingly, peak 1 of the radial forces is also the peak that occurred when the arm was fully extended (around 360° in the propulsion cycle). With a larger sample size or training to more uniformly correct propulsion technique, these inter-participant variations in radial force profiles could be minimized to more accurately characterize changes in force profiles during exercise.

4.3. Limitations

While examining the kinetics of handcycling during HIIT and MICT can give a preliminary idea of the loads experienced by the shoulder during exercise, they are not a direct measurement of shoulder contact forces or joint moments. Thus, it is difficult to know the degree to which hand forces contribute to shoulder loading and therefore injury risk. Arnet reported that lower hand reaction forces in attach-unit handcycling compared to wheelchair propulsion resulted in lower shoulder joint moments (Arnet, 2012). Measuring applied forces at the handcycle handle can therefore give a preliminary indication of loads experienced by the shoulder during exercise and provide an early indication of shoulder injury risk.

The power-based design of the exercise protocol inherently introduces inter-participant variability. Rather than having all participants handcycle at the same power output, the exercise protocols were calibrated to each individual and their fitness level. This was to ensure that the effort levels were similar across participants for each protocol, but did introduce variability in the target PO levels for each exercise. Thus, our analysis of the hand kinetics during handcycling should be interpreted cautiously: the variation we report is an artifact of the design and not necessarily the degree of variability in forces during handcycling in general.

Finally, the participants recruited for this study were all members of the University of Illinois adapted sports teams. Because of this, their exercise rates and fitness levels are likely higher than the average SCI population. We would expect any differences in propulsion style and fatigue observed in these highly trained individuals would be heightened in untrained populations, and thus the differences in propulsion kinetics found in this study would still apply.

5. Conclusion

Handcycling HIIT is associated with higher maximum applied forces in all 3 directions compared to MICT and may indicate that HIIT is associated with higher shoulder contact forces than MICT. Additionally, changes in the location of peak forces (specifically, tangential peak 2 and radial peak 1) may point to altered kinematics from MICT to HIIT at the end of the protocol, potentially due to muscle fatigue which is reflected in increased RPE scores during HIIT compared to MICT. These kinetic and kinematic differences should be further investigated to more fully characterize changes in joint angles during propulsion. With this information, we hope to begin to evaluate injury risk during handcycling HIIT.

Any exercise regimen recommended for PwSCI must also be evaluated for musculoskeletal safety, given their reliance on the upper limbs to perform activities of daily living and high shoulder soft tissue injury rates. Understanding how the applied forces at the handle are changing during a propulsion cycle and throughout an exercise protocol can inform training techniques, exercise development, and safety measures.

CRediT authorship contribution statement

Kellie M. Halloran: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joseph Peters:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Michael D.K. Focht:** Visualization, Validation, Software, Investigation, Data curation. **Ian Rice:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Mariana E. Kersh:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

We have no conflicts of interests to declare.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111672.

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