

Sprinting kinetics and acute muscle potentiation following handcycling exercise in persons with spinal cord injuries

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Abstract

Objectives: Post activation potentiation (PAP) is the phenomenon where muscle force-generating capacity during explosive activities increases after sustained activation. Alternatively, fatigue refers to the decrease in muscle force-generating capacity following sustained activation. The level to which muscles are fatigued or potentiated may influence whether performance is enhanced or decreased. While PAP has been well-documented in able-bodied athletes, few studies have examined PAP and muscle performance following exercise in athletes with spinal cord injuries (SCI). Therefore the objective of this study was to investigate the effect of handcycling exercise on acute muscle performance-defined as total work-and propulsion kinetics in people with SCI.

Design: Within-subject design with repeated measures, n=19 wheelchair users.

Method: We examined the kinetics, power output, and work completed during a maximal effort task (handcycling sprinting) before and after high intensity and moderate intensity exercise to determine the acute effects of different exercise intensities on muscle fatigue and potentiation.

Results: Potentiation (defined as an increase in total work completed during sprinting) was observed after both moderate and high intensity exercise, with more participants potentiated following moderate compared to high intensity. Increases in work completed during the sprints can be traced back to increases in tangential force applied at the handcycle at the beginning of the sprint test.

Conclusions: Most participants were not fatigued following either exercise protocol, which is encouraging for recommending both protocols for people with SCI. Additionally, warm-up exercises for handcycling, especially handcycling sprinting, should be moderate intensity to potentiate the muscles rather than interval cycling or “ramp up” activities.

Keywords: wheelchair, shoulder injuries, muscle fatigue, exercise, adaptive sport, sports for persons with disabilities

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1. Introduction

It is well established that participation in sports improves both fitness and also overall well-being and mental health for persons with spinal cord injuries (PwSCI) [31]. However, while optimizing sports performance has been extensively studied in able-bodied athletes, less is known about improving adaptive sports performance for PwSCI. One type of adaptive sport growing in popularity is handcycling [8]. As adaptive sports and handcycling increase in popularity among PwSCI [13, 12], it is becoming increasingly important to study ways to optimize muscle response for peak performance.

One way to increase performance, especially in explosive activities, is through post-activation potentiation (PAP). PAP is an increase in muscle force generating capacity following muscle use, or conditioning. Enhancement in muscle performance following conditioning has been observed in sprinting [3, 11], cycling [7], rowing [25], and swimming [34]. However, less is known about PAP in PwSCI. Only one study has examined PAP in PwSCI (sitting volleyball athletes), and found a significant increase in peak velocity during bench press throws from PAP, using a conditioning activity of additional bench press throws [15]. While not explicitly testing for PAP, Quittmann et al. investigated handcycling sprinting in able-bodied participants and found an increase in maximum power output following exercise [29, 27], which could be indicative of a potentiated muscle response.

The use of PAP for wheelchair athletes is further complicated by high rates of shoulder overuse injuries and fatigue in this population [35, 6]. In the context of sports performance, fatigue is defined as a decrease in muscle force generating capacity [38, 4, 18, 39], and would be observed via decreased performance post-exercise, usually defined as slower times over the same distance [11] or lower power output [20]. Spinal cord injuries can lead to early-onset muscle fatigue [21], and the increased use of the shoulder during activities of daily living for wheelchair users leads to increased shoulder pain and pathology [6, 5, 2]. Wheelchair athletes must therefore be careful to not over-fatigue their shoulders to the point of injury during training or competition. Exercises that can elicit PAP in PwSCI upon completion of the exercise could therefore put wheelchair athletes at a lower risk for injury post-exercise, as their shoulder muscle capacity is actually improved rather than fatigued when they transfer to a shower or car after a hard exercise session. However, the effect of different training regimen on shoulder muscle response in PwSCI is still unclear.

Muscle fatigue can be observed via changes in kinetics during biking and handrim wheelchair

propulsion. There is evidence that shoulder muscle fatigue results in higher peak handrim forces during wheelchair propulsion [32]. In legged cycling, pedal forces are altered when participants are fatigued, which is related to changes in joint kinematics and kinetics [33]. Quantifying the applied forces during handcycling can provide insight into whether propulsion styles are altered following an exercise protocol.

Understanding the SCI-specific muscle response to different exercise intensities and training routines is an important first step in optimizing adaptive sports performance. The use of PAP to enhance adaptive sport performance has not been examined nearly as extensively as able-bodied athletics. Therefore there is a small but under-served community of PwSCI who are overlooked relative to their able-bodied counterparts.

No studies have evaluated muscle performance in PwSCI before and after handcycling exercise. Therefore, the aim of this study was to investigate the effect of handcycling exercise on acute muscle performance-in this study, defined as work-and propulsion kinetics in PwSCI.

We compared the total work, power output (PO), and applied handle forces of a 15-second sprint test before and after handcycling at two different intensities: moderate intensity continuous training (MICT) high intensity interval training (HIIT). Muscles can be both fatigued and potentiated simultaneously [30] and net muscle performance is a combination of the two. Sprinting performance was quantified using total work and power, and we assume that decreases in performance compared to baseline are indicative of fatigue. We hypothesized that muscles would be more fatigued following high intensity exercise compared to moderate intensity. Additionally, we hypothesized that fatigue would result in a degradation of propulsion technique characterized by an increase in non-propulsive forces (radial and lateral forces) and a decrease in propulsive (tangential) force compared to the baseline sprint.

2. Methods

This study was approved by the Institutional Review Board at the University of Illinois Urbana-Champaign (Approval Number: 21552).

2.1. Participants

Wheelchair athletes were recruited from the University of Illinois adapted sports program following informed consent. All participants had a spinal cord injury or spinal cord dysfunction. Additional inclusion and exclusion criteria can be found in previous work [10].

2.2. Sprint Exercises

All exercises were completed on a recumbent handcycle (Top End, Invacare, USA) adjusted to each participant [19]. An incremental test was used to establish subject-specific peak power output (PPO) levels. The three sprint tests were divided into two exercise sessions on different days (2-10 days apart) (Figure 1).

During the first session, athletes warmed up in the handcycle for five minutes at a self-selected speed and then completed a 15-second maximal effort sprint from a rolling start. Participants rested in the handcycle for 5-10 minutes to recover and then began the HIIT protocol (10 intervals: 1 minute at 90% PPO followed by 1 minute at 10% PPO). Following the HIIT protocol, participants rested for 5-10 minutes until their heart rate (HR) had returned to resting levels at which point they completed an additional 15-second sprint test. Similarly, the second exercise session consisted of a MICT exercise protocol (45% PPO to equivalent workload of HIIT) followed by rest and another 15-second sprint test. Verbal encouragement was given to participants during the sprint tests.

2.3. Work, power output, and determination of potentiation vs fatigue

Power output (PO) was collected during each sprint test using a powermeter on the handcycle hub (2Hz, SRM, Julich, Germany). PO was smoothed with a moving average filter using 12.5% of the data points and integrated with respect to time using a trapezoidal sum (MATLAB, R2021a) to obtain the total work (J) completed during each sprint test.

Percent difference in total work was calculated for the post-MICT and post-HIIT sprints compared to baseline. A $1.5 \times \text{SD}$ improvement in performance has been suggested as a meaningful increase due to PAP [11], where SD is the standard deviation of the performance metric based on the individual athlete's within-subject variation. The within-subject variation for sprint bicycling performance is between 0.7-4.4% [16, 14, 17, 24] and we therefore assumed a maximum within-subject variability of 5%. The threshold for PAP performance enhancement was calculated as 1.5 times the within-subject variability. Thus, a 7.5% improvement in total work completed during the sprint test was considered a result of potentiation. Conversely, we defined a 7.5% decrease in work as evidence of fatigue. Changes in work between -7.5% and 7.5% were considered to be responses with neither potentiation nor fatigue (no effect).

2.4. Kinetics

During the sprints, applied forces and torques were collected using a custom handle instrumented with a six-axis load cell (ATI, Apex, USA, 2000 Hz). Five reflective markers were placed on the handcycle handle and tracked using a 10-camera motion capture system (Vicon Motion Systems, Yarnton, UK, 100 Hz) to determine the crank and handle angle. Forces were decomposed into tangential, radial, and lateral components. Forces from the first complete propulsion cycle after 2.5, 5, and 7.5 seconds of the sprint test were analyzed for each participant.

2.5. Statistical Analyses

Work during each sprint test was tested for normality using the Shapiro-Wilk test. When data were not normally distributed, a Wilcoxon signed ranks test was used to compare work completed during the baseline, post-HIIT, and post-MICT tests (R, v4.4.0). When data were normally distributed, a paired t-test was used.

Statistical non-parametric mapping (SnPM) was used to compare force and PO profiles during sprinting [22]. All SnPM analysis was completed in MATLAB (vR2021a) using the open-source `spm1d` code (v. M.0.4.10) [23]. Data were tested for normality using the D’Agostino-Pearson K2 test, and most were found to be not normally distributed. As a result paired t-tests ($\alpha = 0.05$, number of iterations = 10,000) within the SnPM package were used to compare normality. Tangential, radial, and lateral force profiles during the sprints were compared with SnPM, as well as PO. To reduce the influence of potential instabilities when using SnPM-based analyses, differences shorter than 5% of the total test were ignored [37, 9].

3. Results

Twenty wheelchair athletes (age: 25.5 ± 6.8 years, mass: 63.4 ± 14.4 kg) were recruited for this study. All sessions were completed 4.0 ± 2.6 days apart with no adverse effects. One athlete’s data was removed due to errors during the sprint test data collection, leaving 19 total participants for analysis (Table 1). The 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=7, transverse myelitis n=3, cauda equina syndrome n=1). All participants used wheelchairs as their main mode of transportation.

Table 1: Participant Demographics. Data are mean \pm SD.

n	Sex	Age (years)	BMI	Years living with disability	Mass (kg)
19	9 f	25.47	23.53	19.53	63.43
	10 m	± 7.02	± 4.94	± 5.72	± 14.83

3.1. Power during sprinting

Power vs. time curves were similar between HIIT and baseline sprints across all timepoints (Fig. 2A). MICT sprint PO was 15.4% higher than baseline between 3 and 10.5 seconds ($p < 0.001$), and 7.7% higher than HIIT between 5.5-6 seconds ($p = 0.014$).

3.2. Work

Sprint capacity, defined as total work during the sprint test, was higher than baseline following moderate exercise (median work of 3964 J compared to 3218 J, $p = 0.0001$) (Fig. 2B). Work following high intensity exercise was also higher compared to baseline (median work of 3463 compared to 3218 J, $p = 0.001$). There were no differences in work during sprinting following MICT compared to HIIT.

Most participants (55%) were potentiated, with a median work increase of 11.2% and 8.95% during the sprints following MICT and HIIT compared to baseline, respectively (Table 2, Fig. 2C). Seven participants had no performance effect post-MICT and eight participants exhibited no performance effect post-HIIT. One participant was fatigued following the HIIT protocol and one following the MICT protocol (Table 2).

Table 2: Work and percent increase in work from baseline during each sprint test. Data are median (median absolute deviation). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Trial	Work (J)	% increase from baseline	Number of participants		
			Potentiated	No effect	Fatigued
Baseline	3218 (1381)	-	-	-	-
MICT	3694 (1770)***	11.2 (13.4)	11	7	1
HIIT	3463 (1405)**	8.95 (10.7)	10	8	1

3.3. Kinetics

Force profiles were examined at 2.5, 5, and 7.5 seconds into the sprint, which is where the PO curves were different between MICT and baseline (Figure 2A). Peak tangential forces were largest (Fig. 3A-C), followed by radial forces (Fig. 3D-F) and finally lateral forces (Fig. 3G-I).

The tangential forces following MICT were 19.2%-29.2% higher compared to baseline during the pull phase of the propulsion cycle at 2.5 seconds and 5 seconds of the sprint (Table 3, $p=0.01$ and $0-28^\circ$, $p=0.003$, respectively). Following HIIT, participants applied 27.9% higher tangential forces during sprinting compared to baseline at 5 seconds, again during the pull phase ($0-39^\circ$, $p=0.001$). There were no differences in tangential forces 7.5 seconds into the sprint test following either HIIT or MICT.

The only difference observed in radial forces occurred at 5 seconds into the sprint following HIIT. Radial forces were 58.3% higher than baseline during the pull phase from $0-23^\circ$ ($p=0.005$) (Table 3). No differences in radial forces were observed for MICT. Lastly, the sprint lateral forces after the HIIT sessions were higher than those after MICT and higher compared to baseline lateral forces (Fig. 3G, H, I). At 2.5 seconds, lateral forces were 115% larger than baseline and 295% larger than baseline again at 7.5 seconds into the sprint. Both increases occurred during the pull phase (Table 3). Lateral forces following HIIT were 13.6%-16.8% larger than those after MICT at 5 seconds into the sprint protocol during both the pull ($174-201^\circ$) and push ($251-271^\circ$) phases ($p=0.007$, 0.015 , respectively).

Table 3: Points in the propulsion cycle with significant differences in applied forces. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Force	Time (s)		
	2.5	5	7.5
MICT > Baseline			
F_{tan}	26-62 ^{o*}	0-28 ^{o***}	-
F_{rad}	-	-	-
F_{lat}	-	-	-
HIIT > Baseline			
F_{tan}	-	0-39 ^{o***}	-
F_{rad}	-	0-23 ^{o***}	-
F_{lat}	102-126 ^{o***}	-	101-128 ^{o***}
HIIT > MICT			
F_{tan}	-	-	-
F_{rad}	-	-	-
F_{lat}	-	174-201 ^{o***}	-
		251-271 ^{o*}	

4. Discussion

Understanding the acute muscle response following handcycling exercise can be helpful in (1) refining and safely implementing exercise recommendations for wheelchair users and (2) understanding options for leveraging PAP to improve elite handcycling performance.

4.1. Work and PO

PO values were smaller than those previously reported by Quittmann et al. [29, 27]. The participants in those studies were able-bodied participants who may have been able to use their trunk to generate more power compared to our study population of PwSCI. Quittmann et al. observed a 66% increase in maximum sprinting PO post-exercise [29, 27], which is larger than our observed difference of 9.85%-11.2% increase following HIIT and MICT, respectively. However, their pre-exercise sprint test was completed after a 20-minute familiarization protocol which may have lowered the baseline PO compared to our study.

In our study, a majority of athletes were potentiated following both MICT and HIIT (Table 2, Fig. 2C). 7 participants post-MICT and 8 participants post-HIIT exhibited no effect following exercise. The number of participants that were potentiated, not affected, or fatigued was generally the same between both tests. Each exercise session was tailored to the participant's PPO, which could contribute to the relatively consistent response following HIIT and MICT. Workload was also matched between HIIT and MICT which could impact the consistency of responses post-HIIT and post-MICT.

We know that both protocols facilitate a cardiovascular response in PwSCI [26]. The small fatigue response following each exercise highlights the potential for both handcycling exercises to inducing cardiovascular adaptation without fatiguing the shoulder muscles, an important consideration given the high incidence rates of shoulder injuries in PwSCI [1].

It is important to note that there was one fatigued participant in each of the post-exercise sprints (Table 2). Interestingly, different participants were fatigued which suggests varying individual responses to the exercise protocols. Responses to conditioning and exercise vary between individuals [11], which could be contributing to different individual responses post-exercise. Additionally, the participants in this study had varying levels of spinal cord injury. Although not specifically examined within this study, the heterogeneity across injury levels may have played a role in the heterogeneous responses to exercise. Future studies could examine more

specifically the effect of different conditioning and rest parameters (i.e. different intensities, rest times) and injury levels on fatigue and potentiation during handcycling.

During the post-MICT sprint, participants reached higher power outputs compared to baseline and post-HIIT sprints (Fig. 2A), which suggests a slightly higher potentiation effect following MICT compared to HIIT. This is consistent with previous literature which suggests that moderate intensity conditioning activities are more effective than high intensity at creating a potentiation response [40]. Therefore, warm up exercises for handcycling sprinting could focus on moderate intensity cycling to potentiate the muscles rather than interval cycling or “ramp up” activities. Understanding the effect of exercise intensities on acute muscle performance also has the potential to inform racing strategy. It’s possible that athletes who hold a more continuous pace could elicit a greater sprint response at the end of a race when they need it to win compared to athletes who fluctuate intensities during a race (similar to HIIT).

4.2. Crank Kinetics

Differences in applied kinetics during sprint tests can be helpful in understanding the driving factors behind increased work following MICT and HIIT compared to baseline. Most differences in kinetics occurred at 2.5 and 5 seconds into the sprint. By 7.5 seconds, most of the force profiles (with the exception of the lateral force during the HIIT sprint) were similar to baseline and to each other (Table 3).

Tangential forces contribute to propulsion and measured PO during the sprint test. As expected, the tangential forces were largest during all sprint tests, consistent with previous studies [36]. Muscle potentiation allows participants to generate higher PO—and therefore, complete more work compared to baseline—during the pull phase via increased tangential applied forces. Quittmann et al. suggest that handcycling at higher PO is accomplished by increasing torque production during the pull phase [28]. Similarly, our participants accomplished higher PO during MICT and HIIT sprints compared to baseline by increasing tangential forces during the pull phase (Figure 3A, B).

Interestingly, participants exhibited higher non-propulsive forces (F_{rad} and F_{lat}) during only the post-HIIT sprint (Figure 3E, G, I). While tangential forces were increased in both post-exercise sprints, participants accomplished more work during the MICT sprint by increasing only the tangential forces. Conversely, participants increased the force in all three directions to complete more work during the post-HIIT sprint. It appears that the overall kinetics may

be different following MICT and HIIT, suggesting that individual muscles may be potentiated differently in each protocol. Importantly, non-tangential forces do not contribute to forward propulsion and are thus less desirable from an athletic performance perspective. Future work could involve examining potentiation in specific muscles following handcycling exercise to confirm whether different muscles are potentiated by different conditioning protocols.

At 5.5 seconds into the sprint test, the MICT PO was higher than the HIIT sprint PO (Fig. 2A). It is possible that increased lateral forces at 5 seconds during the HIIT sprint (Fig. 3H) resulted in briefly lower PO during HIIT compared to MICT, although differences in PO between MICT and HIIT sprints were overall minimal.

4.3. Limitations

Baseline testing occurred on the same day as the post-HIIT sprint and 2-10 days before the post-MICT sprint. Within-subject variability and day-to-day variability could therefore affect the comparison of the MICT sprint with the baseline sprint. We have accounted for some of this variability by defining a threshold of $\pm 7.50\%$ for potentiation and fatigue based on existing PAP recommendations [11] and available data about within-subject variability in cycling athletes [16, 14, 17].

It is possible for both fatigue and potentiation to co-exist in muscles [30]. Without a direct measurement of muscle fatigue, it is difficult to differentiate the separate impact of fatigue and potentiation. Nevertheless, an increase in work completed during the sprint tests is still indicative of a net enhanced effect on muscles. Future studies could further examine PAP in PwSCI by directly measuring muscle fatigue and quantifying how much of both fatigue and potentiation is present in the muscles post-exercise.

5. Conclusion

Understanding how handcycling exercise affects propulsion kinetics and muscle fatigue vs potentiation is helpful in preventing shoulder injury risk during exercise for PwSCI. This was the first study to examine PAP in handcycling with PwSCI and represents an important first step in using PAP to improve elite handcycling performance via moderate intensity warm-ups or similar conditioning activities. The fact that most participants (94.7%) were able to maintain or improve their baseline sprint performance indicates low fatigue levels during exercise and is encouraging in pursuing similar exercise protocols for this population in the future. With a

multi-faceted approach to exercise that accounts for both cardiovascular efficacy and shoulder health, we can begin to develop more comprehensive exercise recommendations that improve quality of life and reduce injury risk for PwSCI.

6. Practical Implications

- Muscle potentiation can be used to enhance performance of wheelchair athletes during handcycling sprinting tasks.
- With a better understanding of acute muscle changes following exercise in wheelchair athletes, more tailored exercise and training programs can be developed to strengthen shoulder muscles and improve shoulder function.
- Warm-up exercises for handcycling, especially handcycling sprinting, should be moderate intensity to potentiate the muscles rather than interval cycling or “ramp up” activities.

7. Acknowledgements

Griffin Sipes, Ethan Park, and Danielle Siegel assisted with data collection and processing. Funding was provided by the National Science Foundation. We are grateful for feedback from Dr. Bruce Damon, PhD regarding muscle potentiation.

8. Conflict of Interest

Declarations of interest: none.

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9. Figures

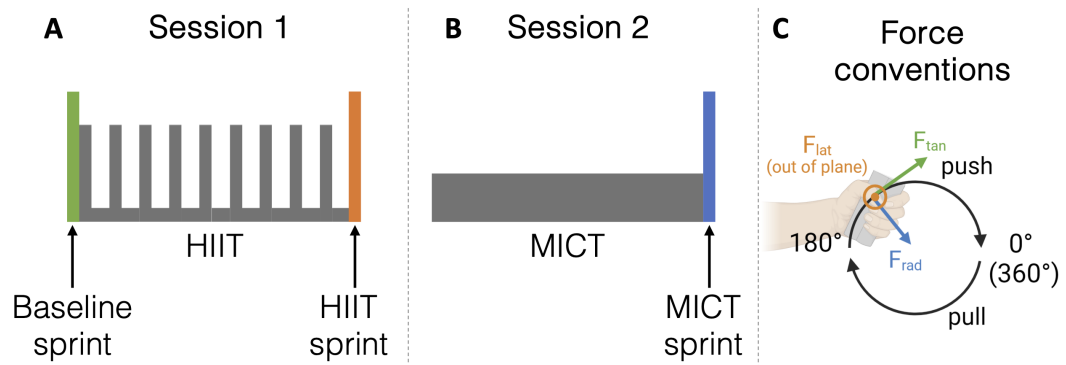


Figure 1: **A, B)** Sprint protocols followed by participants. Each sprint was 15 seconds long. **C)** Propulsion cycle conventions, including positive force directions and push-pull phase designations.

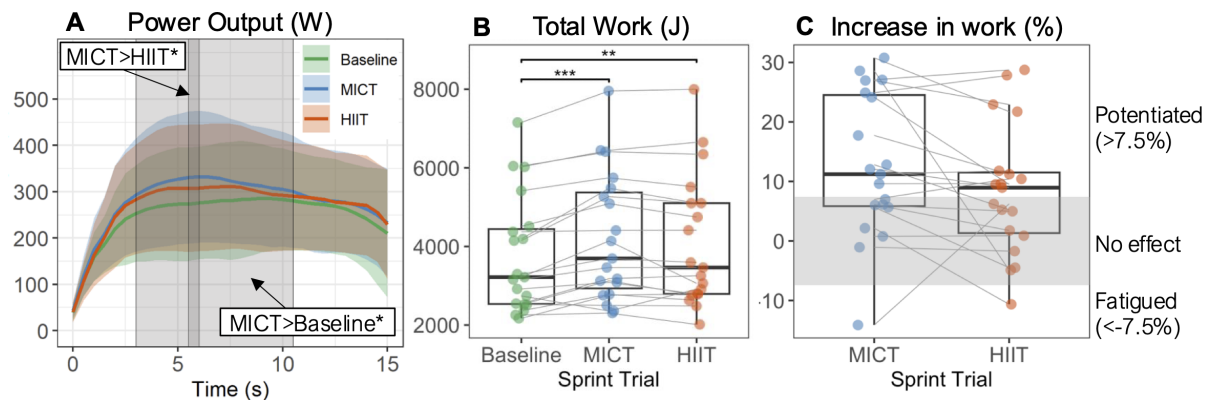


Figure 2: **A)** Power output during the 15-second sprint tests. Solid lines indicate mean and shaded regions indicate standard deviation. Gray shaded boxes indicate significant differences between trials. **B)** Work completed during sprint tests. **C)** Percent increase in work compared to baseline sprint test for post-MICT and post-HIIT tests. Gray lines between boxes connect each participant. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

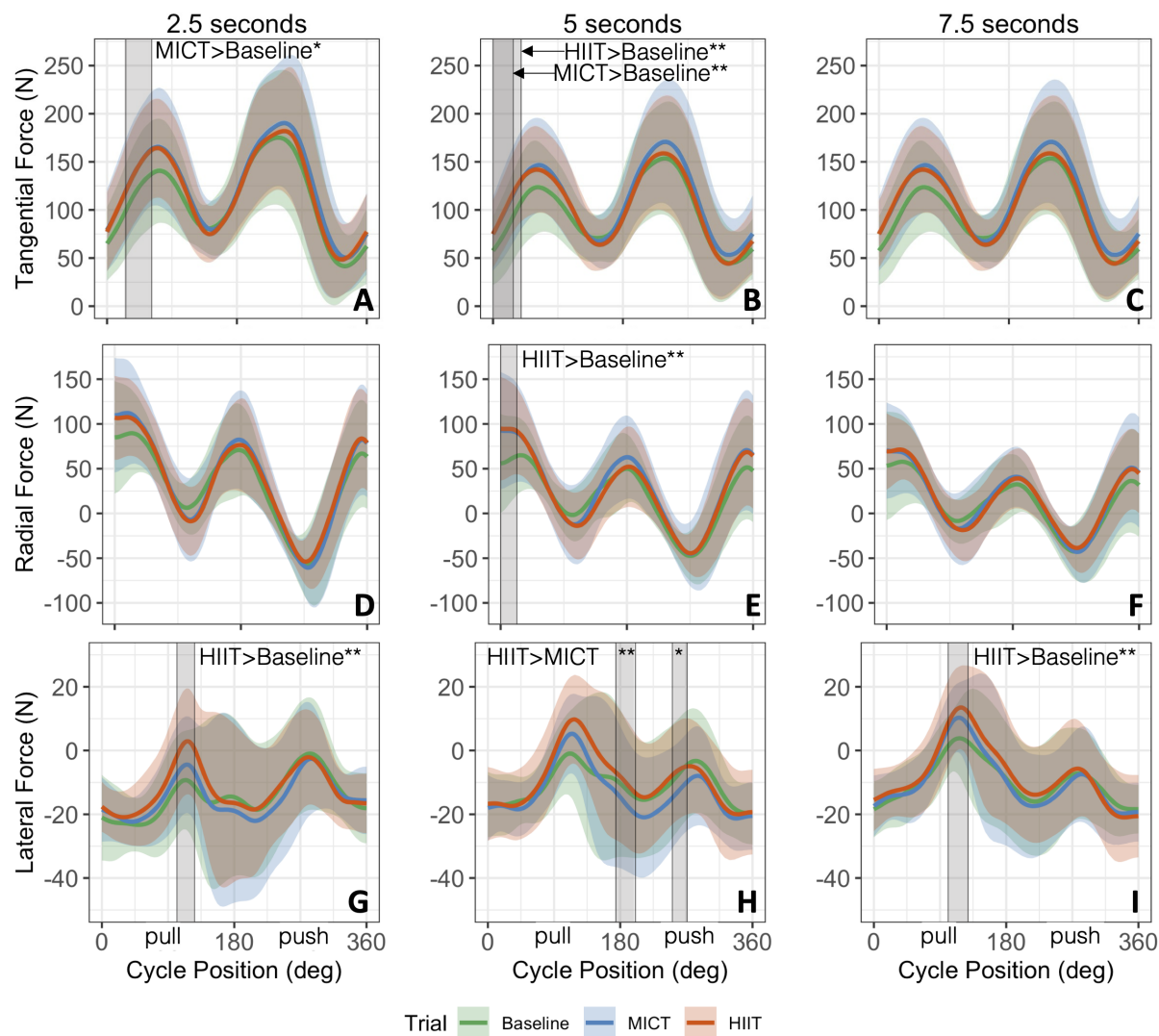


Figure 3: Force profiles during the sprint tests. Solid lines indicate mean and shaded regions indicate standard deviation. Gray shaded regions are significantly different between trials. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.