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Research article

Neuromechanical Differences between Pronated and Supinated Forearm Positions during Upper-Body Wingate Tests

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Abstract

Arm-cycling is a versatile exercise modality with applications in both athletic enhancement and rehabilitation, yet the influence of forearm orientation remains understudied. Thus, this study aimed to investigate the impact of forearm position on upper-body arm-cycling Wingate tests. Fourteen adult males (27.3 ± 5.8 years) underwent bilateral assessments of handgrip strength in standing and seated positions, followed by pronated and supinated forward arm-cycling Wingate tests. Electromyography (EMG) was recorded from five upper-extremity muscles, including anterior deltoid, triceps brachii lateral head, biceps brachii, latissimus dorsi, and brachioradialis. Simultaneously, bilateral normal and propulsion forces were measured at the pedal-crank interface. Rate of perceived exertion (RPE), power output, and fatigue index were recorded post-test. The results showed that a pronated forearm position provided significantly ($p < 0.05$) higher normal and propulsion forces and triceps brachii muscle activation patterns during arm-cycling. No significant difference in RPE was observed between forearm positions ($p = 0.17$). A positive correlation was found between seated handgrip strength and peak power output during the Wingate test while pronated (dominant: $p = 0.01$, $r = 0.55$; non-dominant: $p = 0.03$, $r = 0.49$) and supinated (dominant: $p = 0.03$, $r = 0.51$; don-dominant: $p = 0.04$, $r = 0.47$). Fatigue changed the force and EMG profile during the Wingate test. In conclusion, this study enhances our understanding of forearm position's impact on upper-body Wingate tests. These findings have implications for optimizing training and performance strategies in individuals using arm-cycling for athletic enhancement and rehabilitation.

Key words: Fatigue, arm-cycling, biomechanics, electromyography, force.

Introduction

Arm-cycling is an exercise modality used for athletic performance (Zinner et al., 2016) and rehabilitation (Diserens et al., 2007; Kaupp et al., 2018). The neurophysiological and biomechanical responses of arm-cycling have been of interest in recent years due to its affect on performance improvement and injury prevention (Kraaijenbrink et al., 2021). During arm-cycling, variations such as forearm position (Lockyer et al., 2021a), cycling direction (Lockyer et al., 2021a; Nippard et al., 2020), intensity (Chaytor et al., 2020; Forman et al., 2016; Mravcsik et al., 2021), and work volume (Mravcsik et al., 2021) have been shown to modulate corticospinal excitability which may impact the power output, crank-pedal force production and neuromuscular activity (Chaytor et al., 2020; Lockyer et al., 2023). To the best of our knowledge, no comparison has been performed on arm-cycling with regards to forearm position and their influence on power output, crank-pedal forces and bilateral muscle activity.

Changes in the forearm position (i.e., supinated vs. pronated) during arm-cycling have been shown to produce different amounts of total work output (Krämer et al., 2009), with a pronated forearm position producing greater work output compared to supinated during submaximal arm-cycling (Krämer et al., 2009). The changes in work generation between the pronated versus supinated forearm position could be the result of changes in central nervous system excitability (Forman et al., 2016; 2019). Another study compared the fatiguability of the elbow flexors during backward arm-cycling sprints in pronated and supinated forearm positions and reported that neuromuscular performance indices such as elbow flexor force and potentiated twitch were reduced in the supinated forearm position (Lockyer et al., 2021a). However, very few studies have reported the changes in muscle activation using different forearm positions during cycling. One study reported greater brachioradialis activity in a neutral forearm position compared to supinated and pronated forearm positions (Bressel, 2001) during arm-cycling exercise. Changes in forearm orientation affect elbow flexor muscle lengths and moment arms. These biomechanical changes will influence arm cycling biomechanics and impact power and force generation throughout arm-cycling. Nevertheless, the elucidation of how varying forearm positioning affects muscle activation and force production in the context of arm-cycling remains a subject of inquiry.

Another important consideration during arm-cycling pertains to the impact of arm dominance on neuromechanical outcomes. Even though most arm-cycling studies focus on mechanism in the dominant arm, some research has been conducted on the non-dominant arm (Compton et al., 2022; Lockyer et al., 2019). While studies on arm-cycling have focused on reporting findings on each arm separately, little attention has been given to dominant vs. non-dominant arm comparison. This comparison bears crucial significance, given the reported disparities in upper-extremity strength between the dominant and non-dominant sides (Armstrong and Oldham, 1999; Thorngren and

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Werner, 1979). Thus, difference in force production for pedal propulsion can be postulated to occur between the dominant and non-dominant hand during arm-cycling.

The neuromechanical changes as a result of changing forearm position should be studied via time-series analysis as a previous study has pointed out that neuromuscular responses during arm-cycling is phase dependent (Chaytor et al., 2020). A time-series approach ((i.e., statistical parametric mapping (SPM)), will allow the user to analyze and interpret results throughout the motion, rather than selecting discrete time points of interest. Thus, the aim of our study was to compare the EMG and crank-pedal force profiles, using a time-series approach, between the dominant and non-dominant arm during an upper-body Wingate test with supinated and pronated forearm positions. To our knowledge, this would be the first time a time-series analysis was conducted on the upper-body arm-cycling Wingate. It was hypothesised that during upper-body Wingate tests, the positions of the forearm both supinated and pronated would influence bilateral muscle activity, arm cycling power, and crank-pedal forces.

Methods

Participants

A priori statistical power analysis was conducted based on changes in mean power outputs from a previous study that utilized an arm cycling repeated sprint exercise to examine neuromuscular fatigue (Pearcey et al., 2016). The required sample size was determined and the average sample size number was computed using G*Power 3.1 software (Faul et al., 2007). It was determined that a sample size of 9 was needed to achieve an alpha of 0.05 and a power of 0.8. Therefore, fourteen healthy male adults (age: 27.3 ± 5.8 years; height: 178.8 ± 4.1 cm; weight: 80.8 ± 10.6 kg; BMI: 25.2 ± 3.1 kg•m^{-2}) agreed to participate in this study. All participants were accustomed to maximal bouts of arm-cycling exercise. Participants were queried regarding their injury history through a self-report, specifically focusing on any incidents involving the upper extremity, head, neck, and lower back within the past 12 months. Participants also completed the Edinburgh Handedness Inventory (Oldfield, 1971) to determine their dominant hand. All participants read and signed a written informed consent form prior to participating in the study. The participants were instructed to complete the Physical Activity Readiness Questionnaire Plus (PAR-Q+) and follow the Canadian Society for Exercise Physiology (CSEP, 2003) preliminary instructions (no eating, drinking caffeine, smoking, or alcohol consumption for 2, 2, 2, or 6 h, respectively) prior to the start of testing. Additionally, each participant was asked to refrain from heavy exercise 24 h before testing. The Memorial University of Newfoundland Interdisciplinary Committee on Ethics in Human Research (ICEHR-20200291). All tests and procedures were administered by the same experimenter, with assistance from another experimenter.

Measures

Wingate test exercise protocol

A modified Velotron ergometer (Dynafit Pro, RacerMate, Seattle, Wash., USA) was used to perform the 30-second Wingate test. Participants were seated in a padded armless chair with their feet strapped to the floor. The height of the ergometer was adjusted so that the center of the crankshaft was approximately in line horizontally with the participant's acromion. The padded chair distance was manipulated for each participant and positioned to ensure no reaching was occurring for the arm cranks in full-elbow extension. The hand cranks were locked 180 degrees out-of-phase to perform asynchronous cycling (Figure 1).

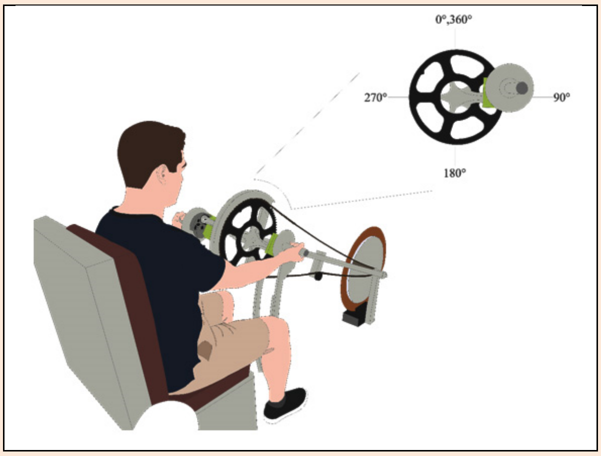

Figure 1. Forward arm-cycling Wingate test in the supinated forearm position on a modified Velotron ergometer. The pedal-crank represents a complete revolution along with its angular displacement.

Participants were situated in front of the cycle ergometer and were asked to complete the exercise protocol. Each sprint began immediately following 10 seconds of cycling at 100 rpm. During the sprints, a torque factor of 5% of the participant's bodyweight in kilograms (kg) was applied by the mechanical brake of the ergometer (Pearcey et al., 2016). Participants were instructed to accelerate following the initiation of the mechanical brake that occurred immediately after a 10-second countdown displayed on Velotron Wingate Software version 1.0 (RacerMate, Seattle, Washington) that was made visible to each participant during the exercise protocol. Participants were instructed to perform each Wingate with a maximal effort until instructed to stop after 30 seconds. Strong verbal encouragement was provided during the exercise protocol. All power output data were recorded using the Monark Wingate Software and stored on a computer. RPM, peak, mean and minimum power (watts) and fatigue index were recorded for each Wingate test (Pearcey et al., 2016).

Handgrip strength

Jamar® Hydraulic Hand Dynamometer was used to assess grip strength from the dominant and non-dominant hand in both seated and standing positions. The grip of the handheld dynamometer was adjusted for everyone so that the base of the device rests on the first metacarpal, while the handle rests on the middle phalanges of the four fingers in accordance with the Canadian Sport Exercise Physiology (CSEP) Physical Activity Training for Health® (CSEP-PATH®). Participants were asked to forcefully and maximally squeeze the dynamometer for ~3-5s. During the standing position, the participants were instructed to hold the hand dynamometer with their palms facing medially and arm slightly abducted. For the seated position, participants' hands were held in the 90° position while seated in the upper-body cycling ergometer. A standard verbal encouragement was given to all participants. The handgrip strength test was completed three times on each hand with 3 minutes of rest between each trial and the highest value was used for further analysis. All handgrip strength values were recoded to the nearest 0.1 kg.

Electromyography (EMG)

Based on SENIAM recommendations (Hermens et al., 2000) EMG recordings were collected from the biceps brachii (BB), lateral head of the triceps brachii (TB), brachioradialis (Br), anterior deltoid (AD), and latissimus dorsi (LD) for the dominant and non-dominant arm using CED 1902 (Cambridge Electronic Designs, Cambridge, United Kingdom) data acquisition system and signal 4 software. A bipolar configuration of disposable Ag-AgCl surface EMG electrodes (10 mm diameter; MediTrace™ 130 Foam Electrodes Massachusetts, USA) were positioned 2 cm apart (center-to-center) over the mid-point of the muscle belly for each muscle. A ground electrode was placed over the lateral epicondyle. The skin was shaved, abraded, and cleaned using an alcohol swab prior to electrode placement. EMG data was collected using CED 1902 (Cambridge Electronic Designs), amplified (×1000) and band-pass filtered using a 3-pole Butterworth filter with cutoff frequencies of 10–1000 Hz. An interelectrode impedance of <5 kΩ was obtained prior to recording to ensure an adequate signal-to-noise ratio. All signals were analog-digitally converted at a sampling rate of 2 kHz using a CED 1401 (Cambridge Electronic Design Ltd., Cambridge, UK) interface.

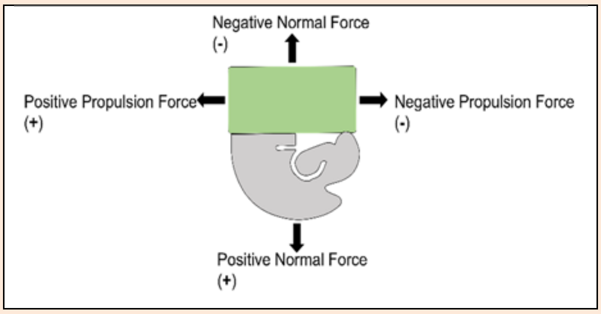

Figure 2. Normal and propulsion force orientations. Positive Propulsion Force is the force driving the pedals in a clockwise direction. Negative Propulsion Force is the force driving the pedals in a counterclockwise direction. Positive Normal Force is the force that is applied perpendicularly downward relative to the pedal-crack junction. Negative Normal Force is the force that is applied perpendicularly upward relative to the pedal-crack junction.

Crank-pedal forces

Time series normal and propulsion crank-pedal forces were measured using the Powerforce (Smartfit, Radlabor GmbH, Freiburg, Germany) mounted on the right and left pedals. For each session the Powerforce was calibrated by positioning the virtual arm crank (an off set of 12° from the actual crank arm) to the vertical and horizontal (relative to the floor) for the normal and propulsion forces respectively. Recordings were completed at 500 Hz and forces were recorded to the nearest 0.01 N. The orientation of the vector forces is presented in Figure 2.

RPE

Rate of perceived exertion was obtained after the exercise protocol using the Borg scale (Borg, 1982). Participants rated their subjective exercise intensity from a scale of 6–20; six being equivalent to complete rest and 20 being equivalent maximum effort.

Design and Procedures

Experimental protocol

A repeated-measures study design was utilized where participants were asked to visit the lab on two separate occasions for 1) familiarization session to become accustomed to the experimental set-up and 2) the experimental session. For the familiarization session, participants became accustomed to the upper-body Wingate test in both pronated and supinated forearm positions (Figure 1). Furthermore, participants practiced the handgrip strength tests in both seated and standing positions. During the experimental session, during midday, participants performed an exercise protocol consisting of 2 separate upper body Wingate tests interspersed by 30 minutes of rest. Prior to completing the Wingate Tests, the handgrip dynamometer test was randomly administered on the participants dominant and non-dominant hands in both seated and standing positions. Following the handgrip strength test, EMG electrodes were placed over desired muscles. Once the EMG set-up was completed participants performed a warmup on the arm cycling ergometer at 25W for 5 minutes at 60 rpm. After the warm-up, participants randomly completed two 30-second Wingate tests (Figure 3). In a randomized order, one Wingate test was performed with the participants gripping the hand crank with a supinated forearm position and the other with a pronated forearm position. After each Wingate test the RPE was recorded.

Data analyses

EMG and force data were time synchronised from the start to the end of the resisting phase of the Wingate test. Both EMG and force data were degree normalized to one complete cycling revolution (i.e., 360°) starting from the 0° position. EMG data were normalized to the peak values, which were averaged and obtained from the root mean square (RMS) during the Wingate protocol for each muscle. Afterwards the EMG data was processed using a RMS rolling window of 100 frames. A 4th order dual lowpass Butterworth filter with a 20 Hz cut-off was applied to crank-pedal forces. The EMG and force data were grouped into beginning, middle, end revolutions by averaging three cycling revolutions of their respective duration of the Wingate. The beginning is considered the average of three complete revolution of the upper-body Wingate test. The middle was defined as the average three revolution at the half-way point of the Wingate test. Additionally, the end was defined as the last three revolution of the upper-body Wingate test. Fatigue index was calculated by custom Velotron software by subtracting the minimum wattage from peak wattage and dividing it by the peak wattage.

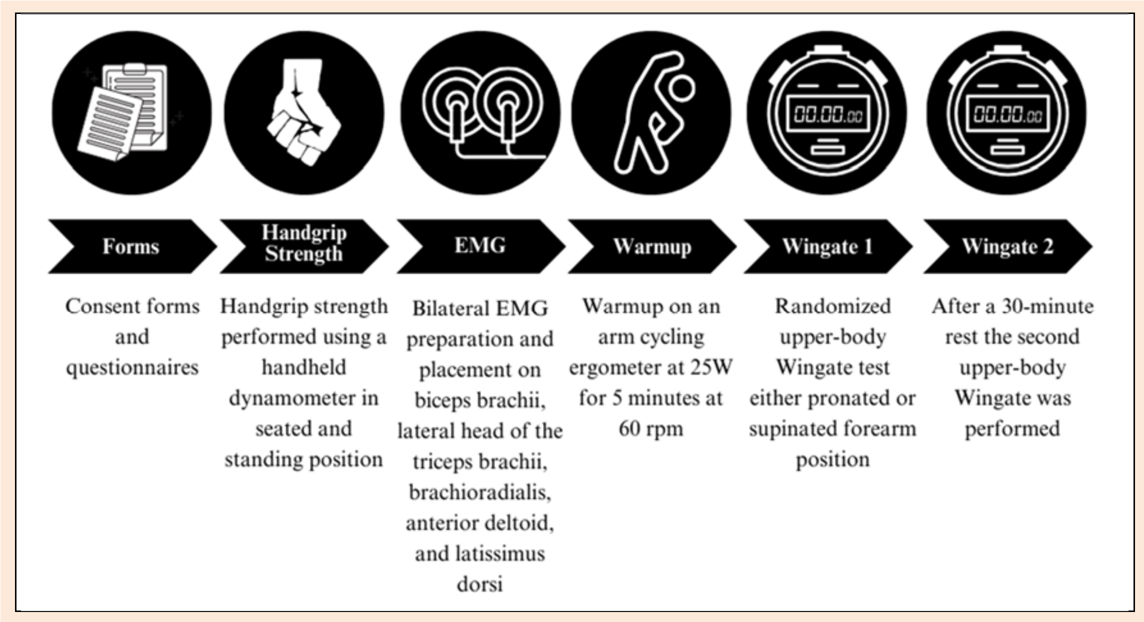

Figure 3. Test procedure flowchart.

Statistical analyses

All statistics were performed in SPSS (IBM version 21). Normality of the data were assessed using Shapiro-Wilk test and SPM package via MATLAB. The following statistical analyses were conducted using the SPSS software. Paired sample t-test was used to compare the RPE, cycling power outputs (peak, minimum and average), and fatigue index between the supinated and pronated arm-cycling position. Handgrip strength was assessed using a two-way, within-subject factors (handedness, standing vs. sitting) repeated measures ANOVA. Levene's test was additionally performed to ensure that the assumption of equal variances was met for the repeated measures ANOVA test. A two-tailed Pearson correlation was used to determine the relationship between handgrip strength and cycling power output. The Pearson correlation coefficient (r) was employed to measure the strength of the correlation between variables. Effect sizes were classified as small (0.1), medium (0.3), large (0.5), and very large (0.7) based on the magnitude of the correlation. The Intraclass Correlation Coefficient (ICC) was employed to evaluate the repeatability of the handgrip strength measurement.

The following analyses were conducted using the SPM package developed for time-series analysis in MATLAB (Pataky, 2010). A two-tailed Pearson correlation was used to determine the relationship between handgrip strength for each hand in both seated and standing position with crank-pedal force outputs during the upper-body Wingate tests (supinated and pronated). EMG (supinated vs. pronated) and crank-pedal force (supinated vs. pronated) were statistically analyzed using a three-way, within-subject factors (handedness, revolutions, rorearm position) repeated measures ANOVA. A Bonferroni adjustment was set for multiple comparisons and alpha levels were set at $p < 0.05$. Time-series data are reported in figures and tables showing the magnitude and length (range) of changes.

Results

Wingate Test Power Outputs and Handgrip Strength

The pronated forearm position produced greater peak (↑5%; $t(13) = 3.38$; $p < 0.01$, Cohen's-d = 0.87), average (↑8.5%; $t(13) = 4.82$; $p < 0.01$, Cohen's-d = 1.12), and minimum (↑11.6%; $t(13) = 3.91$; $p < 0.01$, Cohen's-d = 0.98) power outputs compared to the supinated forearm position during the upper-body Wingate test. There was no effect of forearm position on fatigue index during the upper-body Wingate tests ($t(13) = 0.53$; $p = 0.6$).

A high degree of reliability was achieved for the standing (ICC = 0.82, $p < 0.001$) and seated (ICC = 0.91, $p < 0.001$) handgrip strength test. There were no significant main effects for position or handedness on handgrip strength ($p > 0.05$). However, there were significant positive correlations between handgrip strength (in the seated position for both the dominant and non-dominant hands) and peak power outputs during both supinated (dominant: $p = 0.03$, $r = 0.51$; don-dominant: $p = 0.04$, $r = 0.47$) and pronated (dominant: $p = 0.01$, $r = 0.55$; non-dominant: $p = 0.03$, $r = 0.49$) forearm position upper-body Wingate tests (Table 1), but not between handgrip strength and crank pedal forces ($p > 0.05$).

Table 1. Pearson correlation and p-value results between peak power output measures during upper-body Wingate test and handgrip strength test

	NDHC	DHC	NDHS	DHS
Pronated	r = 0.36, p = 0.1	r = 0.24, p = 0.2	r = 0.49, p = 0.03*	r = 0.55, p = 0.01*
Supinated	r = 0.362, p = 0.1	r = 0.32, p = 0.13	r = 0.47, p = 0.04*	r = 0.51, p = 0.03*

NDHC: Non-dominant hand conventional; DHC: Dominant hand conventional; NDHS: Non-dominant hand seated; DHS: Dominant hand seated; * represents a significant correlation p < 0.05.

EMG profile during pronated and supinated upper-body Wingate tests

Tables 2 and 3 report all SPM non-observed and observed effects for changes in EMG and pedal crank forces during pronated and supinated upper-body Wingate tests. Below, the main findings are briefly summarized.

Biceps brachii

A main effect was found for revolutions (Table 2) with the post-hoc test revealing greater biceps brachii activity during revolutions at the end of the Wingate test followed by less activity during the beginning revolutions compared to the middle and end revolutions (Figure 4, Table 3). Similar patterns of activity and less activity were seen between the middle vs. end revolutions (Figure 4, Table 3). The modulation of muscle activity during upper-body Wingate test depended on the cycling revolution phase. In the initial 180°, the amplitude increased from the beginning to last revolutions. Conversely, biceps brachii activity exhibited a decrease in amplitude during the last 180° from the beginning to last revolutions.

Table 2. Significant clusters detected via SPM for interaction and main effects for EMG activity and force production during upper-body Wingate during pronated and supinated forearm position in dominant and non-dominant hand.

	Revolutions	Handedness	Forearm Position	Revolutions* Handedness	Revolutions* Forearm Position	Handedness* Forearm Position	Revolutions* Handedness* Forearm Position
Biceps Brachii	52°-186.3° (p<0.001); 250.7° -346.1° (p<0.001)	NS	NS	NS	NS	NS	NS
Triceps Brachii	59.8° -115.8° (p<0.001); 127.9°–128.3° (p = 0.05); 204.4°–242.8° (p<0.001); 246.4°–321.7° (p<0.001)	NS	92.1° – 122.4° (p = 0.001)	NS	NS	NS	NS
Brachial Radialis	0 – 6° (p = 0.045); 61.5°–187.6° (p<0.001); 254.5° – 360° (p<0.001)	NS	NS	110.4° – 112.2° (p = 0.049)	NS	NS	151.9° – 152° (p = 0.049)
Latissimus Dorsi	0° – 17.2° (p=0.017); 68.4°–135.8° (p<0.001); 217.5°–285.7° (p<0.001)	NS	NS	NS	NS	NS	320.8° – 322.2° (p = 0.049); 323.4° – 331° (p = 0.04); 337.5° – 340.3° (p = 0.049)
Anterior Deltoid	10.1°–107.6° (p<0.001); 179.1°–313.8° (p<0.001)		299.5° – 313.3° (p=0.029)				222.2° – 224.5° (p = 0.049)
Normal	27.6°–67° (p = 0.002); 117.4°–201.8° (p<0.001); 284.8°–339.1° (p<0.001)	NS	0° – 35.6° (p = 0.003); 332.3°-360° (p = 0.011)	10.3° – 55.4° (p = 0.001)	0° – 22.6° (p = 0.018); 303.8° – 360° (p<0.001)	0°–4.6° (p = 0.048); 319.5°–360° (p = 0.002)	195.7° – 220.1° (p = 0.015); 338° – 355° (p = 0.028)
Propulsion	0° – 360° (p < 0.001)	16.5° – 81.1° (p = 0.001); 135.6° – 152.3° (p = 0.03); 209.8° – 245.1° (p = 0.015); 275° – 329° (p = 0.003)	0° – 104.6° (p < 0.001); 291.9° – 295° (p = 0.05); 338° – 360° (p = 0.032)	45.5° – 72° (p = 0.026); 221.8° – 244.9° (p = 0.031); 289.4° – 339.6° (p = 0.005)	0° – 109.3° (p < 0.001); 177.7° – 213.8° (p = 0.015); 278.8° – 292.6° (p = 0.042); 335.1° – 360° (p = 0.03)	0° – 50.5° (p = 0.004); 208.6° – 283.5° (p<0.001); 318.7° – 360° (p = 0.01)	241.6° – 281.3° (p = 0.012)

NS: non-significant (i.e., p > 0.05).

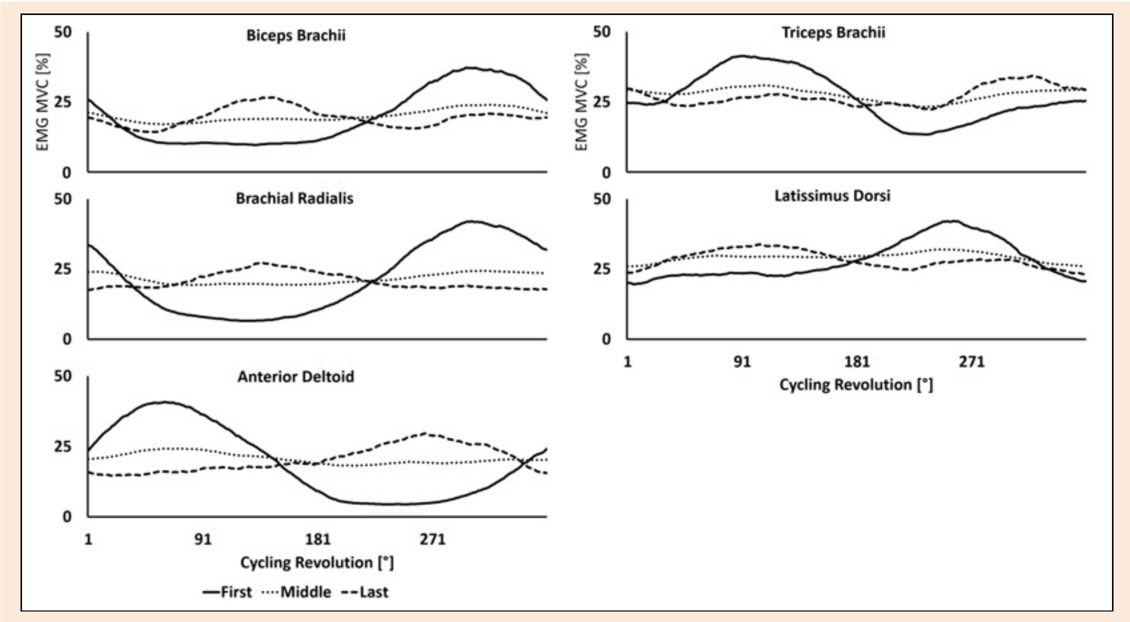

Figure 4. **Muscle activity of biceps brachii, triceps brachii, brachioradialis, latissimus dorsi, and anterior deltoid during the first, middle and last cycling revolution of an upper-body Wingate test.**

Table 3. **Significant clusters detected for post-hoc testing of the main effects for EMG activity and force production during upper-body Wingate during pronated and supinated forearm position in dominant and non-dominant hand.**

	Revolutions	Handedness	Forearm Position
Biceps Brachii	B v. M: 31.4° – 194.3° (p<0.001); 250.7° – 347.6° (p<0.001)	NS	NS
	B v. E: 63.9° – 183.3° (p<0.001); 245.1° – 345° (p<0.001)		
	M v. E: 133.6° – 149.3° (p = 0.008)		
Triceps Brachii	B v. M: 62° – 146.3° (p<0.001); 195.3° – 304.8° (p<0.001)	NS	55° – 127.5° (p<0.001)
	B v. E: 59.3° – 144.9° (p<0.001); 204.9° – 322° (p<0.001)		
Brachial Radialis	B v. M: 0° – 5.4° (p = 0.015); 45.4° – 188.3° (p<0.001); 254° – 360° (p<0.001)	NS	NS
	B v. E: 0 – 11.8 (p=0.011); 65.3° – 183.6° (p<0.001); 251.5° – 360° (p<0.001)		
Latissimus Dorsi	B v. M: 0° – 143.8° (p<0.001); 222.5° – 295.2° (p<0.001); 352° – 360° (p = 0.012)	NS	NS
	B v. E: 36.6° – 64.9° (p = 0.016); 66.2° – 130.8° (p<0.001); 212° – 288.4° (p<0.001)		
	M v. E: 213.6° – 229.2° (p = 0.004)		
Anterior Deltoid	B v. M: 9.8° – 112.7° (p<0.001); 162.7° -321.2° (p<0.001)	NS	251.1° – 330.6° (p<0.001)
	B v. E: 6.4° – 117.1° (p<0.001); 180.7° – 316.7° (p<0.001)		
	M v. E: 34.1° – 87.2° (p<0.001); 243.9° – 287.7° (p<0.001)		
Normal	B v. M: 114° – 206.9° (p<0.001); 277° – 329.9° (p<0.001)	NS	0° – 39.1° (p=0.003); 264.5° – 276.2° (p = 0.039); 316.7° – 360° (p = 0.002)
	B v. E: 31.1° – 68.9° (p = 0.001); 153.2° – 203.1° (p<0.001); 288.5° – 338.2° (p<0.001)		
Propulsion	B v. M: 0°-360° (p <0.001)	7.6° – 90.8° (p < 0.001); 112.3° – 174.8° (p < 0.001); 200.7° – 252.7° (p = 0.001); 270.2° – 339.2° (p < 0.001)	0° – 118.5° (p < 0.001); 164.5° – 219.1° (p = 0.001); 275.2° – 307° (p = 0.012); 331° – 360° (p = 0.017)
	B v. E: 0°-360° (p <0.001)		
	M v. E: 0°-360° (p <0.001)		

NS: non-significant (i.e., p > 0.05); B: beginning revolutions; M: middle revolutions; E: end revolutions

Triceps brachii

Main effects were found for revolutions and forearm position (Table 2). The post-hoc analysis showed greater triceps activity during the initial degrees of cycling revolution followed by a greater activity reduction in the beginning revolutions compared to the middle and end revolutions (Figure 4, Table 3). Similarly, the pronated forearm position resulted in higher triceps activity in the beginning cycling revolution compared to the supinated forearm position (Figure 5, Table 3). In contrast with biceps brachii muscle activity, the triceps brachii exhibited a reduction in muscle activity in throughout the first 180° from the beginning to last revolutions. Additionally, from the beginning to last revolutions the amount of triceps activity increased over the duration of the Wingate test.

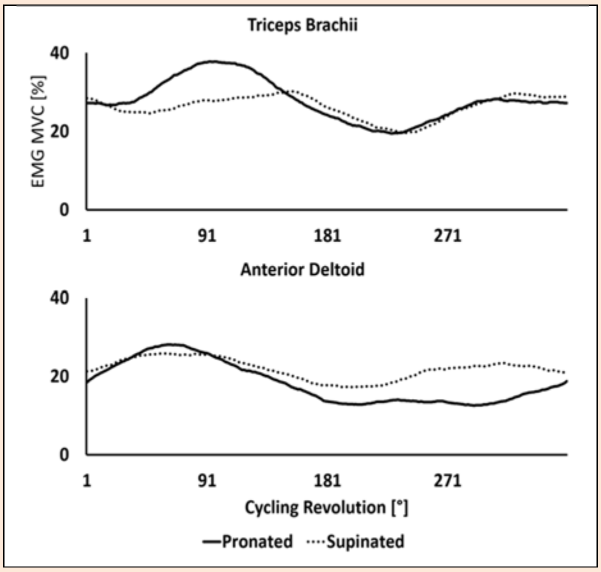

Figure 5. Muscle activity of triceps brachii, and anterior deltoid in the pronated and supinated forearm position during an upper-body Wingate test.

Brachioradialis

An interaction effect was observed for handedness*revolutions and handedness*revolutions*forearm position (Table 2). A main effect was found for revolutions where the post-hoc results showed greater brachioradialis activity at the end of the revolution cycle followed by a less activity during the beginning revolutions compared to the middle and end revolutions (Figure 4, Table 3). The brachioradialis exhibited a similar modulation in muscle activity to the biceps brachii over the Wingate test. In the initial 180°, the amplitude increased from the beginning to last revolutions. Conversely, brachioradialis activity exhibited a decrease in amplitude during the last 180° from the beginning to last revolutions.

Latissimus dorsi

An interaction effect was observed for handedness*revolutions*forearm position (Table 2) where the non-dominant hand in the supinated forearm position showed a greater activation during the last quarter of the cycling revolution in the end revolution. A main effect was found for revolutions (Table 2), with the post-hoc test depicting a less EMG activity in the first quarter followed by greater activity in the beginning revolutions compared to the middle and end revolutions (Figure 4, Table 3). Similar patterns of activity and less activity can be seen between the middle vs. end revolutions (Figure 4, Table 3). While the activity modulation followed a similar trend as the biceps brachii and brachioradialis, there were differences in the magnitude of change. In the initial 180°, the amplitude increased from the beginning to last revolutions. Conversely, latissimus dorsi activity exhibited a decrease in amplitude during the last 180° from the beginning to last revolutions.

Anterior Deltoid

An interaction effect was observed for handedness*revolutions*forearm position (Table 2) where the non-dominant hand showed greater activity in the end revolutions in the supinated position in the mid portions of a cycling revolutions. A main effect was found for revolutions and forearm position (Table 2). The post-hoc test showed a significant increase in activity while in supinated compared to pronated forearm position (Figure 4, Table 3). Additionally, the post-hoc analysis showed higher anterior deltoid activity during the initial degrees of cycling revolution followed by a greater activity reduction in the beginning revolutions (Figure 4, Table 3). Similar patterns of activity and less activity can be seen between the middle vs. end revolutions (Figure 4, Table 3). Interestingly, the anterior deltoid muscle activity followed a trend similar to that of the triceps brachii. The anterior deltoid exhibited a reduction in muscle activity throughout the first 180° from the beginning to last revolutions. Additionally, triceps brachii activity increased from the beginning revolutions to last revolutions throughout the Wingate test.

Crank-pedal force production during pronated and supinated upper-body Wingate tests

Tables 2 and 3 summarize all SPM non-observed and observed effects for changes in pedal crank forces during pronated and supinated upper-body Wingate tests.

Normal

A significant interaction was observed for forearm position*revolution. The pronated forearm position produced a greater normal force during the first and last quarter of pedaling during the beginning revolutions (Table 2). Furthermore, an interaction effect for forearm position*handedness was observed. The dominant hand produced greater upward normal force during the last degrees of pedaling in the pronated forearm position (Table 2). Additionally, during the first quarter of pedaling in the supinated forearm position the non-dominant hand produced greater downward normal force (Table 2). An interaction effect for revolution*handedness was observed where the non-dominant hand produced greater downward force in the first quarter of the cycling revolution during the beginning revolutions (Table 2). Moreover, an interaction effect for forearm position*revolution*handedness was found where the pronated forearm position had higher and lower downward and upward normal force production, respectively, during the end revolutions in the second half of the cycle (Table 2).

Main effects were found for forearm position and revolution (Table 2). The post-hoc test revealed a greater upward normal force (the pedal force changes its orientation throughout a cycling revolution) production during the last quarter of the cycling revolution in the pronated forearm position, whereas during the first quarter of the cycling revolution the supinated forearm position exhibited greater downward normal force (Table 3, Figure 6). Additionally, while approaching the last quarter of the cycling revolution the pronated forearm position produces greater downward force compared to the supinated forearm position (Table 3, Figure 6). During the second quarter and fourth quarter of the cycling revolution the beginning revolutions produce greater upward normal force compared to the middle revolutions. Moreover, during the first quarter of the revolution cycle the beginning revolutions produced greater downward normal force compared to the end revolutions (Table 3, Figure 6). Furthermore, during the second and fourth quarter of the cycling revolution a greater upward force was produced in the beginning revolutions compared to the end revolutions (Table 3, Figure 6).

Propulsion

A significant interaction effect was observed for forearm position*revolution. During first quarter of the revolution cycle the pronated forearm position produced greater pushing force at the beginning revolutions (Table 2). During the third quarter of the cycle revolution the supinated position produced greater pulling force in the beginning revolutions (Table 2). During the fourth quarter of the cycle revolution the supinated position exhibited greater pushing force initially, however subsequently the pronated position produced greater pushing force in the beginning revolutions (Table 2).

An interaction effect was determined for forearm position*handedness for the first quarter of cycling revolution where the dominant hand showed a greater pushing force while in pronated forearm position (Table 2). Additionally, the third quarter for the cycling revolution the dominant hand produced greater pulling force in the supinated forearm position (Table 2). Furthermore, during the fourth quarter of the revolution cycle the non-dominant hand produced greater pushing force in the pronated position (Table 2).

There was an interaction effect for revolution*handedness was observed where in the first quarter the dominant hand produced greater pushing force in the beginning revolutions (Table 2). Additionally, during the third quarter of cycling revolution the dominant hand produced greater pulling force in the beginning revolutions (Table 2). Moreover, the fourth quarter of the cycling revolution produced greater pulling force in the supinated forearm position but was overtaken by the pronated forearm position in pulling force production in the beginning revolutions (Table 2). Lastly, there was an interaction effect for forearm position*revolution*handedness where the supinated forearm position produced greater force interchangeably between the dominant and non-dominant arm (Table 2).

A main effect was found for forearm position, revolution and handedness (Table 2). Post-hoc test showed a significant difference where the pronated forearm position produced greater pushing force from 0° - 118.5° (Table 3, Figure 6) of the cycling revolution. Additionally, from 164.5° - 219.1° of the cycling revolution, the supinated forearm position produced greater pulling force (Table 3, Figure 6). Furthermore, from 275.2° - 307° of the cycling revolution, supinated forearm position produced greater pushing force, whereas from 331° - 360° of the cycling revolution, pronated forearm position produced greater pushing force (Table 3, Figure 6).

During the first quarter of the cycle revolution the dominant hand produced greater pushing force whereas during the second quarter of cycling revolution the non-dominant hand produced greater pulling force (Table 3, 6).

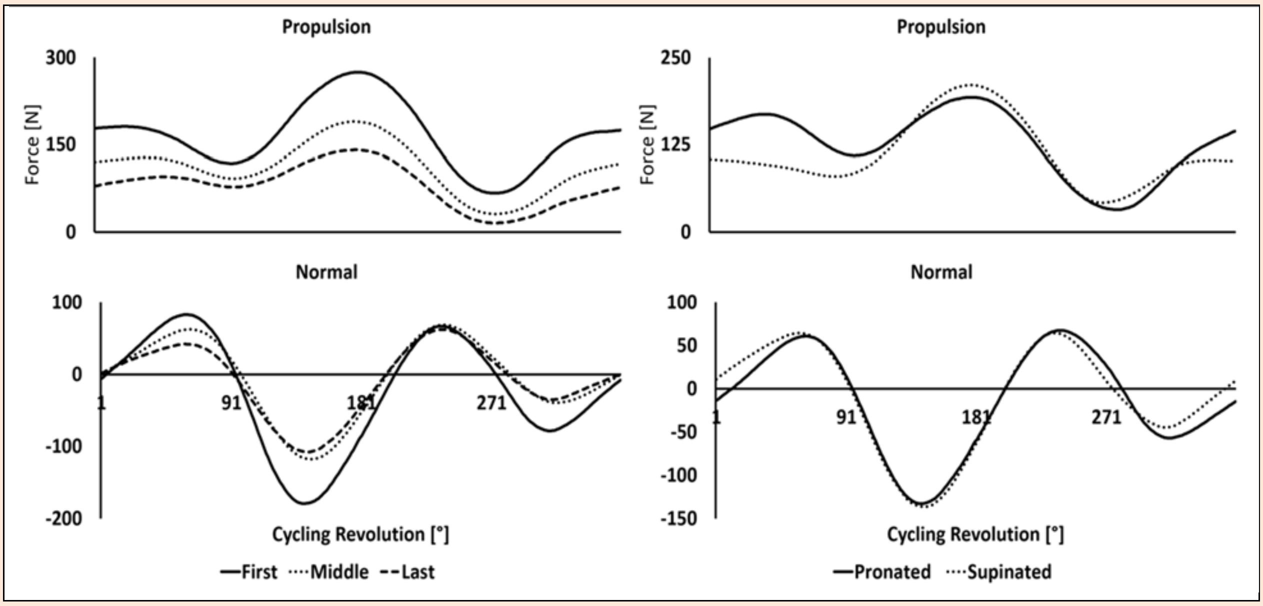

Figure 6. Normal and propulsion crank-pedal forces during an upper-body Wingate. The first column on the left represents the normal and propulsion force changes during the first, middle, and last revolutions of an upper-body Wingate test. The second column to the right, exhibit the normal and propulsion force changes in the supinated and pronated forearm position during an upper-body Wingate test.

During the third quarter of the of the cycling revolution the dominant hand produced greater pulling force, however it

Propulsion

A significant interaction effect was observed for forearm position*revolution. During first quarter of the revolution cycle the pronated forearm position produced greater pushing force at the beginning revolutions (Table 2). During the third quarter of the cycle revolution the supinated position produced greater pulling force in the beginning revolutions (Table 2). During the fourth quarter of the cycle revolution the supinated position exhibited greater pushing force initially, however subsequently the pronated position produced greater pushing force in the beginning revolutions (Table 2).

An interaction effect was determined for forearm position*handedness for the first quarter of cycling revolution where the dominant hand showed a greater pushing force while in pronated forearm position (Table 2). Additionally, the third quarter for the cycling revolution the dominant hand produced greater pulling force in the supinated forearm position (Table 2). Furthermore, during the fourth quarter of the revolution cycle the non-dominant hand produced greater pushing force in the pronated position (Table 2).

There was an interaction effect for revolution*handedness was observed where in the first quarter the dominant hand produced greater pushing force in the beginning revolutions (Table 2). Additionally, during the third quarter of cycling revolution the dominant hand produced greater pulling force in the beginning revolutions (Table 2). Moreover, the fourth quarter of the cycling revolution produced greater pulling force in the supinated forearm position but was overtaken by the pronated forearm position in pulling force production in the beginning revolutions (Table 2). Lastly, there was an interaction effect for forearm position*revolution*handedness where the supinated forearm position produced greater force interchangeably between the dominant and non-dominant arm (Table 2).

A main effect was found for forearm position, revolution and handedness (Table 2). Post-hoc test showed a significant difference where the pronated forearm position produced greater pushing force from 0° - 118.5° (Table 3, Figure 6) of the cycling revolution. Additionally, from 164.5° - 219.1° of the cycling revolution, the supinated forearm position produced greater pulling force (Table 3, Figure 6). Furthermore, from 275.2° - 307° of the cycling revolution, supinated forearm position produced greater pushing force, whereas from 331° - 360° of the cycling revolution, pronated forearm position produced greater pushing force (Table 3, Figure 6).

During the first quarter of the cycle revolution the dominant hand produced greater pushing force whereas during the second quarter of cycling revolution the non-dominant hand produced greater pulling force (Table 3, 6). During the third quarter of the of the cycling revolution the dominant hand produced greater pulling force, however it gets overtaken by the non-dominant hand in the fourth quarter of the cycling revolution by producing greater pushing force (Table 3, Figure 7).

gets overtaken by the non-dominant hand in the fourth quarter of the cycling revolution by producing greater pushing force (Table 3, Figure 7).

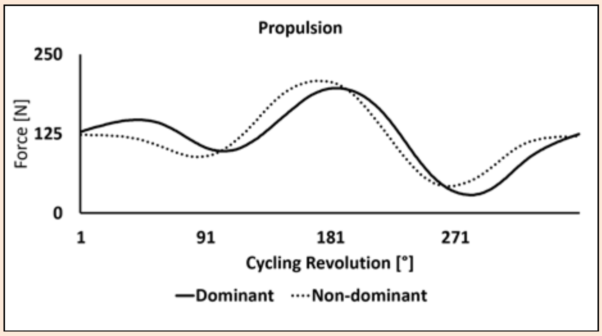

Figure 7. Propulsion force in the dominant and non-dominant hand during an upper-body Wingate test.

During the entire cycling revolution, the beginning revolutions produced greater propulsion force compared to the middle and end revolutions (Table 3, Figure 6). Additionally, the middle revolutions produced greater propulsion force compared to the end revolutions (Table 3, Figure 6).

Rate of Perceived Exertion (RPE)

RPE was not significantly ($t(13) = 0.92$, $p = 0.17$) different between supinated and pronated (17.1 ± 0.1 vs. 16.1 ± 0.1, respectively) upper-body Wingate tests.

Discussion

The most important finding from this study was that forearm position influenced the amount of force being produced at the pedal-crank junction during an upper-body Wingate test. In part, these changes may be due to neuromechanical changes in muscle length and moment arm of the muscles crossing the elbow joint. Correspondingly, these biomechanical changes influence muscle activity. Thus, the development of fatigue and neuromechanical changes during the Wingate test influences the level of muscle activity and are influenced by forearm position. When altering forearm position in the upper-body Wingate test, supinated forearm positioning reduced propulsion force in the test's final revolutions. Handedness impacted muscle activity and crank-pedal force production during the Wingate test with different forearm positions and at different stages of the test. These results suggest that forearm position can affect muscle activation in an upper-body Wingate test.

Wingate Test Performance

Our results demonstrate that in the pronated forearm position, higher peak, average, and minimum power outputs were produced compared to the supinated position. These findings agree with Lockyer et al. (2021a,b) where they suggested that modifications in task (i.e., forearm position) will alter the neuromechanical profile during a supinated forearm arm-cycling sprint compared to a pronated arm-cycling sprint. Furthermore, our results revealed a moderate positive correlation between grip strength in the seated position and peak power outputs in both dominant and non-dominant hands during the supinated and pronated forearm position upper-body Wingate. While differences were observed in muscle activity and force and power production between supinated and pronated forearm position; these did not influence the rate of perceived exertion between the two forearm positions as they were reported to have equal amount of exertion. While pronated forearm positioning resulted in greater power production, there was no difference in fatigue index between forearm positions. The absence of a difference may stem from the similar minimum-to-peak power production in both forearm positions. This suggests that changes in forearm position may not affect relative cycling metrics such as fatigue index, but rather absolute values such as power production.

Changes in EMG during the Wingate Test

Our findings show that during an upper-body 30-second Wingate test, the amount of muscle activity in the biceps brachii, triceps brachii, brachioradialis, anterior deltoid, and latissimus dorsi decreased as the Wingate progressed from start to finish. These findings may, in part, be explained by changes in the supraspinal and spinal activity. A previous study showed that after repeated 10-second arm-cycling sprints motor evoked potentials (MEPs) were reduced by roughly 40% while the cervicomedullary motor evoked potentials (CMEPs) increased by 28% (Pearcey et al., 2016). The authors concluded that fatigue, as a result of upper-body arm-cycling sprints, decreased the supraspinal excitability while concomitantly reducing the spinal excitability. It was suggested that upper-body arm-cycling sprints inhibits the supraspinal drive to the muscles, causing a reduction in motor output resulting in decreased performance. Nonetheless, it is imperative to underscore that the EMG findings from Pearcey et al. (2016) were acquired both preceding and following upper-body arm-cycling sprints executed within the context of an isometric maximum voluntary contraction, a condition characterized by distinct muscle recruitment patterns and biomechanical demands when juxtaposed with the act of arm-cycling.

Furthermore, our study demonstrated that muscle activity undergoes dynamic variations across distinct phases of the arm-cycling revolution (ranging from 0° to 360°), contingent upon factors such as forearm orientation, handedness, and the developmental stages of the arm-cycling task. These observations align with previous findings (Chaytor et al., 2020), which observed alterations in integrated EMG amplitude during the flexion and extension phases of arm-cycling movement. However, it is worth noting a pivotal distinction in our investigation, as Chaytor and colleagues did not undertake a comparative analysis of the effects pertaining to forearm position and the influence of fatigue on EMG outcomes (Chaytor et al., 2020). It is suggested that the EMG amplitude increases at the initial stages of fatigue (Dimitrova and Dimitrov, 2003), however most of these reports are from submaximal fatiguing tasks. During maximal fatiguing tasks, the amplitude of the surface EMG has been reported to decrease with time (González-Izal et al., 2012), which partially supports the results of our experiment. Additionally, our findings revealed that muscle activity during an upper-body Wingate is dependent on both fatigue and cycling phase. Selected muscles adjust their activity levels based on the degree of fatigue and the specific phase of cycling. While the biceps brachii, brachioradialis, and latissimus dorsi exhibited an increase in activity during the initial 180° from the beginning to the end of the Wingate test, the triceps brachii, along with the anterior deltoid, displayed a decrease in activity during the same cycling phase. Alternatively, during the last 180° the triceps brachii and the anterior deltoid exhibited an increase in muscle activation during the Wingate, while biceps brachii, brachioradialis, and latissimus dorsi showed a decrease. This demonstrates the intricate interplay between cycling phase and fatigue level during the upper-body Wingate test.

This might be a result of the increased susceptibility of the triceps barchii and brachioradialis to early occurrence of fatigue during upper-body Wingate. The increased fatigue susceptibility to fatigue in the triceps brachii lateral head may stem from its primary role as a synergist in elbow extension, whether in supinated or pronated positions. Compared to the other heads of the triceps brachii, the lateral head fatigues later (Ali et al., 2015), which justifies the observed increase in fatigability during the middle and end revolutions. These findings are in contrast with that of Pearcey et al. (2016) where they did not find a difference in the RMS EMG activity of biceps brachii and triceps brachii during the time-course of 10, 10-s arm-cycling sprints. One clear distinction for this discrepancy can be related to the method of acquiring EMG data between the two experiments. Where Pearcey et al. (2016) recorded the EMG during an isometric elbow flexion after each bout of 10-s arm-cycling sprint, this study recorded the EMG during the arm-cycling sprint. The disassociation between the fatiguing task and EMG measures in Pearcey's study would allow for ample peripheral recovery (Froyd et al., 2013; 2020). Thus, future studies should try to assess EMG during similar and not different tasks.

The forearm position did influence the anterior deltoid and triceps brachii activity during an upper-body Wingate. The anterior deltoid showed greater activity during the pushing phase in the supinated forearm position compared to the pronated forearm position. Similar results were achieved when comparing the activity of the anterior deltoid in a flexed shoulder position to pronated and supinated forearm positions (Ijiri et al., 2020). It was determined that forearm position does influence scapular muscle activity while in a flexed position, by increasing the anterior deltoid activation in the supinated forearm position. While our results show a greater triceps brachii activity in the pronated forearm position during the pushing stages, another study showed greater triceps brachii activity in a pronated forearm position during an isometric task (Buchanan et al., 1989). The discrepancy between results could be related to arm position where the difference in triceps brachii activation can be seen. It has been shown that a change in shoulder flexion angle can contribute to changes in triceps barchii activity (Kholinne et al., 2018). Given the triceps brachii lateral head's role as the synergist elbow extensor, it is reasonable to hypothesize that during various phases of the arm-cycling revolution, this muscle is likely to be engaged in actions related to elbow extension movements.

Compared to the other heads of the triceps, the lateral head mainly functions as a synergist during elbow extension and as such it is insufficient at producing force during elbow flexion (Kholinne et al., 2018). Biomechanically, a supinated forearm will increase the biceps brachii and brachioradialis moment arm during flexion, thus increasing the mechanical advantage (Murray et al., 1995). Since upper-body arm-cycling is a dynamic task, the increase in elbow flexion angle during the pulling phase will further alter flexion moment arms. However, in our work, the propulsion force still remained greater in the supinated forearm position. During the pulling phase, the propulsion force while in the supinated forearm position exceeded the pronated forearm position. The increased propulsion force along with similar biceps brachii and brachioradialis activity would suggest that the supinated forearm position during the pulling phase has a greater neuromechanical advantage compared to the pronated forearm position.

One interesting finding from this study was the effect that forearm position and cycling revolution had on latissimus dorsi activity of the non-dominant arm. It was shown that the supinated forearm position during the end cycling revolutions in the non-dominant hand had greater activity. This could possibly be explained through the fatigue onset that the upper-body Wingate has on the latissimus dorsi, where the amplitude of the EMG signal increases (Jørgensen et al., 1988). Since no main effects of handedness and forearm position was observed for latissimus dorsi activity, it can be derived that fatigue had a major role in the increased activity. Even though both brachioradialis and anterior deltoid showed an interaction effect for forearm position and revolution on EMG activation, the cluster window that was deemed statistically different was very small (in some cases ~ 1°) thus making an argument in small angle ranges difficult.

When visually examining the muscle activation, the biceps brachii, brachioradialis and latissimus dorsi are activated throughout the same regions of a cycling revolution (i.e., second half of flexion phase). Similarly, the anterior deltoid along with the triceps brachii are mostly activated within the same regions (i.e., second half of the elbow extension phase). This finding can illustrate that during an upper-body Wingate, muscles such as the biceps brachii, brachioradialis and latissimus dorsi can be considered synergists whereas the anterior deltoid and triceps brachii are each others' synergists.

Changes in crank pedal forces during the Wingate Test

Regarding the normal crank-pedal force, the pronated forearm position produced a greater upward force compared to the supinated forearm position during the pushing stages of the cycling revolution. The upward force is relative to the position of the force measuring unit mounted between the crank and pedal, thus contributing to a pushing motion where the pedal gets propelled forward. However, the supinated forearm position normal force overtakes the pronated forearm normal force as the cycling revolution enters the pushing phase producing more downward force contributing to the propulsion of the pedal. By considering the main muscle contributors (i.e., triceps brachii and anterior deltoid) we found that during the pushing stage the anterior deltoid has lower muscle activity in the pronated forearm position. This could suggest that with lower muscle activity and greater forces, there is increased neuromuscular advantage of the anterior deltoid in the pronated position. Similarly, the triceps brachii showed lower activity during the pushing stage in the supinated forearm position, which can be justified through greater neuromuscular advantage within that cycling revolution stage. A constant reduction in the normal force can be observed from the beginning to the end revolutions throughout the entire cycling revolution apart from the second half of the pulling stage. As individuals progress through the arm-cycling task, the force applied to the pedals gradually decreases from the beginning revolutions to the end revolutions.

The propulsion force, tangential to the pedal, represents a uniform change compared to the normal force. The propulsion force constantly decreases from the beginning cycling revolutions to the middle and end revolutions. These results indicate that the onset of fatigue occurs between the beginning and middle revolutions of the upper-body Wingate test regardless of hand position and handedness. Past studies have shown that multiple upper-body arm-cycling sprints will decrease the maximum isometric elbow flexion force as a result of fatigue (Collins et al., 2018; Lockyer et al., 2021a), however the method of measurement was disassociated with the task which undermines ecological validity (Power et al., 2022). Additionally, during the cycling revolution, the contribution to the propulsion force from each hand shifts during the upper-body Wingate test.

When the cycling revolution is dissected into four quarters, for each quarter only one hand is the main force generator. For example, within the first quarter of the cycling revolution (i.e., 0° - 90°) the dominant hand produced greater propulsion force. Simultaneously, the non-dominant hand did not produce greater propulsion force during the third quarter of the cycling revolution (i.e., 180° - 270°). This result can illustrate that even though both dominant and non-dominant arms are producing propulsion force during upper-body Wingate, at any given section of the cycling revolution, one arm would be the main driver while the opposite arm assists the propulsion. Another interesting finding is that as the action of pulling (90° - 270°) and pushing (270° - 90°) during arm-cycling transitions between one another, the non-dominant arm produces a greater amount of propulsion force during the first half of each respective phase (pushing and pulling), and subsequently is overtaken by the dominant arm. The exact underlying mechanisms behind this strategy of force production is not yet known and further studies are required.

The most prominent effect of forearm position was found in propulsion force production. During most of the pushing phase, the pronated forearm position had a greater propulsion force whereas during most of the pulling phase, the supinated forearm position produced higher propulsion force. The greater propulsion force could be associated with heightened corticospinal excitability of the biceps brachii during a supinated forearm position in the pulling phase. It was found during arm-cycling that the neutral (i.e., more supinated) forearm position had a greater corticospinal activity in the 180° position (i.e., mid-pulling phase) compared to the pronated forearm position (Forman et al., 2016). This is in contrast with the results from Forman et al. (2016) where no difference was observed in supraspinal and spinal excitability of the biceps brachii regardless of forearm position and elbow flexion angle. The main contrast between the two previously mentioned studies were the task, where one carried out a dynamic task (i.e., arm-cycling) and the other an isometric task. It has been shown that central nervous system excitability is also task dependent (Forman et al., 2014; 2016; Lockyer et al., 2021b), which could partially explain the difference between the studies. The increased corticospinal activity may potentially lead to greater propulsion force production without the increased EMG activity of the elbow flexors, suggesting increased neuromuscular advantage in the supinated forearm position during the pulling phase.

The relationship between grip strength and Wingate test power production

With regards to handgrip strength, no difference in grip force was observed between the seated and conventional standing position. These findings are in line with previous reports (Elsais and Mohammad, 2015). The absence of correlation between the standing handgrip strength test and Wingate test power metrics suggests lower ecological validity between these two tasks. This is contrary to the seated position results where moderate correlation was observed between the handgrip strength results and Wingate test power metrics. Historically, handgrip strength is considered an overall functional strength indicator, applicable across both male and female populations (Kuh et al., 2005). Diminished handgrip strength has exhibited significant correlations with reduced overall physical performance, a phenomenon that may have implications for the output power generated during arm-cycling endeavors. It appears that handgrip strength stands as a promising indicator of upper-body anaerobic power during the act of arm-cycling.

Methodological considerations

While participants did acquaint themselves with upper-body cycling, the novelty of the task could have hindered their proficiency in arm cycling. In addition, this work did not compare sex effects on crank-pedal force production or EMG measures during upper-body Wingate test. It has been reported that males produce greater power output during upper-body Wingate test compared to females (Weber et al., 2006), which can arise from anatomical and morphological differences in body composition. The study acknowledges the potential limitation of conducting two Wingate tests in a single session with a 30-minute rest interval. This design may have introduced fatigue as a confounding variable, potentially influencing the performance outcomes of the second test. Despite randomization of the testing order, it is recognized that this may not have fully mitigated the impact of fatigue. Future research could consider conducting the tests in separate sessions to eliminate this potential confounder.

Conclusion

In conclusion, this study has provided valuable insights into the intricate relationship between forearm position, muscle activation patterns, crank-pedal force production, and handgrip strength during upper-body Wingate tests. The findings emphasize the critical role that forearm position plays in modulating force production at the pedal-crank junction, with distinct advantages observed in both pronated and supinated forearm positions during different phases of the cycling revolution. While the supinated forearm position demonstrated superior neuromechanical efficiency in terms of propulsion force production during the pulling phase, the pronated forearm position exhibited greater upward force generation during the pushing stages. The subtle nuances in forearm positioning strategies illuminate the potential advantages of customizing these techniques to enhance performance during distinct phases of upper-body Wingate tests. This tailored approach proves particularly valuable for individuals managing spinal lesions, allowing for targeted muscle engagement. Furthermore, it offers a means to accommodate and navigate functional limitations, ultimately promoting the acquisition of enhanced functional abilities. Additionally, the study underscores the significance of handgrip strength as a potential predictor of upper-body anaerobic power, particularly in the seated position, highlighting its relevance as an indicator of overall physical performance.

Furthermore, the investigation revealed dynamic changes in muscle activation patterns across distinct phases of the arm-cycling revolution, influenced by factors such as forearm orientation, handedness, and fatigue onset. The observed reductions in EMG activity as the Wingate test progressed may reflect alterations in supraspinal and spinal excitability, providing insights into the neuromuscular fatigue profile during upper-body cycling. Overall, this research advances our knowledge of upper-body Wingate test performance and offers valuable insights for athletes, coaches, and researchers seeking to optimize training and performance strategies in this context.

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References

Ali, S., Sundaraj, K., Ahmad, R. B., Ahamed, N. U., Islam, A. and Sundaraj, S. (2015) Muscle Fatigue in the Three Heads of the Triceps Brachii During a Controlled Forceful Hand Grip Task with Full Elbow Extension Using Surface Electromyography. *Journal of Human Kinetics* **10**(46), 69-76. https://doi.org/10.1515/hukin-2015-0035

Armstrong, C. A. and Oldham, J. A. (1999) A comparison of dominant and non-dominant hand strengths. *Journal of Hand Surgery (Edinburgh, Scotland)* **24(4)**, 421-425. https://doi.org/10.1054/jhsb.1999.0236

Bressel, E. (2001) The influence of ergometer pedaling direction on peak patellofemoral joint forces. *Clinical Biomechanics* **16(5)**, 431-437. https://doi.org/10.1016/S0268-0033(01)00009-2

Buchanan, T. S., Rovai, G. P. and Rymer, W. Z. (1989) Strategies for muscle activation during isometric torque generation at the human elbow. *Journal of Neurophysiology* **62(6)**, 1201-1212. https://doi.org/10.1152/jn.1989.62.6.1201

Chaytor, C. P., Forman, D., Byrne, J., Loucks-Atkinson, A. and Power, K. E. (2020) Changes in muscle activity during the flexion and extension phases of arm cycling as an effect of power output are muscle-specific. *PeerJ* **8**, e9759. https://doi.org/10.7717/peerj.9759

Collins, B. W., Pearcey, G. E. P., Buckle, N. C. M., Power, K. E. and Button, D. C. (2018) Neuromuscular fatigue during repeated sprint exercise: Underlying physiology and methodological considerations. *Applied Physiology, Nutrition, and Metabolism* **43(11)**, 1166-1175. https://doi.org/10.1139/apnm-2018-0080

Compton, C. T., Lockyer, E. J., Benson, R. J. and Power, K. E. (2022) Interhemispheric inhibition is different during arm cycling than a position- and intensity-matched tonic contraction. *Experimental Brain Research* **240(9)**, 2425-2434. https://doi.org/10.1007/s00221-022-06413-8

Dimitrova, N. A. and Dimitrov, G. V. (2003) Interpretation of EMG changes with fatigue: Facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology* **13(1)**, 13-36. https://doi.org/10.1016/S1050-6411(02)00083-4

Diserens, K., Perret, N., Chatelain, S., Bashir, S., Ruegg, D., Vuadens, P. and Vingerhoets, F. (2007) The effect of repetitive arm cycling on post stroke spasticity and motor control: Repetitive arm cycling and spasticity. *Journal of the Neurological Sciences* **253(1-2)**, 18-24. https://doi.org/10.1016/j.jns.2006.10.021

Elsais, W. and Mohammad, W. (2015) Influence of different testing postures on hand grip strength. *European Scientific Journal* **10**, 1857-7881.

Faul, F., Erdfelder, E., Lang, A.-G. and Buchner, A. (2007) G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods* **39(2)**, 175-191. https://doi.org/10.3758/BF03193146

Forman, D. A., Monks, M. and Power, K. E. (2019) Corticospinal excitability, assessed through stimulus response curves, is phase-, task-, and muscle-dependent during arm cycling. *Neuroscience Letters* **692**, 100-106. https://doi.org/10.1016/j.neulet.2018.11.003

Forman, D. A., Richards, M., Forman, G. N., Holmes, M. W. R. and Power, K. E. (2016) Changes in Corticospinal and Spinal Excitability to the Biceps Brachii with a Neutral vs. Pronated Handgrip Position Differ between Arm Cycling and Tonic Elbow Flexion. *Frontiers in Human Neuroscience* **10**. https://doi.org/10.3389/fnhum.2016.00543

Forman, D., Raj, A., Button, D. C. and Power, K. E. (2014) Corticospinal excitability of the biceps brachii is higher during arm cycling than an intensity-matched tonic contraction. *Journal of Neurophysiology* **112(5)**, 1142-1151. https://doi.org/10.1152/jn.00210.2014

Froyd, C., Beltrami, F. G., Millet, G. Y., MacIntosh, B. R. and Noakes, T. D. (2020) Greater Short-Time Recovery of Peripheral Fatigue After Short- Compared With Long-Duration Time Trial. *Frontiers in Physiology* **11**, 399. https://doi.org/10.3389/fphys.2020.00399

Froyd, C., Millet, G. Y. and Noakes, T. D. (2013) The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. *The Journal of Physiology* **591(5)**, 1339-1346. https://doi.org/10.1113/jphysiol.2012.245316

González-Izal, M., Malanda, A., Gorostiaga, E. and Izquierdo, M. (2012) Electromyographic models to assess muscle fatigue. *Journal of Electromyography and Kinesiology* **22(4)**, 501-512. https://doi.org/10.1016/j.jelekin.2012.02.019

Hermens, H. J., Freriks, B., Disselhorst-Klug, C. and Rau, G. (2000) Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology* **10(5)**, 361-374. https://doi.org/10.1016/s1050-6411(00)00027-4

Ijiri, T., Urabe, Y., Maeda, N., Sasadai, J. and Suzuki, T. (2020) Comparative study of the differences in shoulder muscle activation according to arm rotation angle. *Human Movement Science* **69**, 102567. https://doi.org/10.1016/j.humov.2019.102567

Jørgensen, K., Fallentin, N., Krogh-Lund, C. and Jensen, B. (1988) Electromyography and fatigue during prolonged, low-level static contractions. *European Journal of Applied Physiology and Occupational Physiology* **57(3)**, 316-321. https://doi.org/10.1007/BF00635990

Kaupp, C., Pearcey, G. E. P., Klarner, T., Sun, Y., Cullen, H., Barss, T. S. and Zehr, E. P. (2018) Rhythmic arm cycling training improves walking and neurophysiological integrity in chronic stroke: The arms can give legs a helping hand in rehabilitation. *Journal of Neurophysiology* **119(3)**, 1095-1112. https://doi.org/10.1152/jn.00570.2017

Kholinne, E., Zulkarnain, R. F., Sun, Y. C., Lim, S., Chun, J.-M. and Jeon, I.-H. (2018) The different role of each head of the triceps brachii muscle in elbow extension. *Acta Orthopaedica et Traumatologica Turcica* **52(3)**, 201-205. https://doi.org/10.1016/j.aott.2018.02.005

Kraaijenbrink, C., Vegter, R. J. K., Ostertag, N., Janssens, L., Vanlandewijck, Y., van der Woude, L. H. V. and Wagner, H. (2021) Steering Does Affect Biophysical Responses in Asynchronous, but Not Synchronous Submaximal Handcycle Ergometry in Able-Bodied Men. *Frontiers in Sports and Active Living* **3**, 741258. https://doi.org/10.3389/fspor.2021.741258

Krämer, C., Hilker, L. and Böhm, H. (2009) Influence of crank length and crank width on maximal hand cycling power and cadence. *European Journal of Applied Physiology* **106(5)**, 749-757. https://doi.org/10.1007/s00421-009-1062-1

Kuh, D., Bassey, E. J., Butterworth, S., Hardy, R., Wadsworth, M. E. J. and and the Musculoskeletal Study Team. (2005) Grip Strength, Postural Control, and Functional Leg Power in a Representative Cohort of British Men and Women: Associations With Physical Activity, Health Status, and Socioeconomic Conditions. *The Journals of Gerontology: Series A* **60(2)**, 224-231. https://doi.org/10.1093/gerona/60.2.224

Lockyer, E. J., Alizadeh, S., Compton, C. T., Button, D. C. and Power, K. E. (2023) Two weeks of arm cycling sprint interval training enhances spinal excitability to the biceps brachii. *Journal of Applied Physiology* **134(6)**, 1422-1437. https://doi.org/10.1152/japplphysiol.00367.2022

Lockyer, E. J., Buckle, N. C. M., Collins, B. W. and Button, D. C. (2021a) Neuromuscular fatigue of the elbow flexors during repeated maximal arm cycling sprints: The effects of forearm position. *Applied Physiology, Nutrition, and Metabolism* **46(6)**, 606-616. https://doi.org/10.1139/apnm-2020-0519

Lockyer, E. J., Compton, C. T., Forman, D. A., Pearcey, G. E., Button, D. C. and Power, K. E. (2021b) Moving forward: Methodological considerations for assessing corticospinal excitability during rhythmic motor output in humans. *Journal of Neurophysiology* **126(1)**, 181-194. https://doi.org/10.1152/jn.00027.2021

Lockyer, E. J., Nippard, A. P., Kean, K., Hollohan, N., Button, D. C. and Power, K. E. (2019) Corticospinal Excitability to the Biceps Brachii is Not Different When Arm Cycling at a Self-Selected or Fixed Cadence. *Brain Sciences* **9(2)**, Article 2. https://doi.org/10.3390/brainsci9020041

Mravcsik, M., Botzheim, L., Zentai, N., Piovesan, D. and Laczko, J. (2021) The Effect of Crank Resistance on Arm Configuration and Muscle Activation Variances in Arm Cycling Movements. *Journal of Human Kinetics* **76**, 175-189. https://doi.org/10.2478/hukin-2021-0053

Murray, W. M., Delp, S. L. and Buchanan, T. S. (1995) Variation of muscle moment arms with elbow and forearm position. *Journal of Biomechanics* **28(5)**, 513-525. https://doi.org/10.1016/0021-9290(94)00114-J

Nippard, Anna. P., Lockyer, Evan. J., Button, Duane. C. and Power, Kevin. E. (2020) Corticospinal excitability to the biceps and triceps brachii during forward and backward arm cycling is direction- and phase-dependent. *Applied Physiology, Nutrition, and Metabolism* **45(1)**, 72-80. https://doi.org/10.1139/apnm-2019-0043

Oldfield, R. C. (1971) The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* **9(1)**, 97-113. https://doi.org/10.1016/0028-3932(71)90067-4

Pataky, T. C. (2010) Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics* **43(10)**, 1976-1982. https://doi.org/10.1016/j.jbiomech.2010.03.008

Pearcey, G. E. P., Bradbury-Squires, D. J., Monks, M., Philpott, D., Power, K. E. and Button, D. C. (2016) Arm-cycling sprints induce neuromuscular fatigue of the elbow flexors and alter corticospinal excitability of the biceps brachii. *Applied Physiology, Nutrition, and Metabolism* **(2)**, 199-209. https://doi.org/10.1139/apnm-2015-0438

Power, K. E., Lockyer, E. J., Botter, A., Vieira, T. and Button, D. C. (2022) Endurance-exercise training adaptations in spinal motoneurones: Potential functional relevance to locomotor output and assessment in humans. *European Journal of Applied Physiology* **122(6)**, 1367-1381. https://doi.org/10.1007/s00421-022-04918-2

Thorngren, K.-G. and Werner, C. O. (1979) Normal Grip Strength. *Acta Orthopaedica Scandinavica* **50(3)**, 255-259. https://doi.org/10.3109/17453677908989765

Weber, C. L., Chia, M. and Inbar, O. (2006) Gender differences in anaerobic power of the arms and legs - A scaling issue. *Medicine and Science in Sports and Exercise* **38(1)**, 129-137. https://doi.org/10.1249/01.mss.0000179902.31527.2c

Zinner, C., Morales-Alamo, D., Ørtenblad, N., Larsen, F. J., Schiffer, T. A., Willis, S. J., Gelabert-Rebato, M., Perez-Valera, M., Boushel, R., Calbet, J. A. L. and Holmberg, H.-C. (2016) The Physiological Mechanisms of Performance Enhancement with Sprint Interval Training Differ between the Upper and Lower Extremities in Humans. *Frontiers in Physiology* **7**. https://doi.org/10.15561/26649837.2021.0605

Key points

- While the supinated forearm position demonstrated superior neuromechanical efficiency in terms of propulsion force during the pulling phase, the pronated forearm position exhibited greater upward force during the pushing stages.
- The potential advantages of customizing these techniques to enhance performance with upper-body cycling could be specifically valuable for individuals managing spinal lesions, allowing for targeted muscle engagement. Hence, it allows for accommodation to navigate functional limitations.
- Additionally, the study emphasizes the significance of handgrip strength as a potential predictor of upper-body anaerobic power, particularly in the seated position, highlighting its relevance as an indicator of overall physical performance.
- The observed reductions in EMG activity as the Wingate test progressed may reflect alterations in supraspinal and spinal excitability.

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