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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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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