Quantifying the Bilateral Deficit in Force During Maximal Arm Cycling Wingates.

By

©Philip Francis Edwards

201714243

A thesis submitted to the

School of Graduate Studies

In partial fulfilment of the requirements of the degree of

Master of Science in Kinesiology

School of Human Kinetics and Recreation

Memorial University of Newfoundland

August 2023

St. John's Newfoundland and Labrador

Abstract

The bilateral deficit phenomenon (BLD) is a reduction in performance during a bilateral motor task when compared to the performance during the unilateral version of the same motor task. The objective of the current study was to determine if there was a BLD during maximal arm cycling Wingate tests. Thirteen healthy male participants performed three 30-second maximal arm cycling Wingate tests during three experimental sessions. Each session the participants completed Wingate tests with 1) both arms, 2) dominant arm, and 3) non-dominant arm at randomized intensities including 3% body weight (BW), 4% BW, or 5% BW. Instantaneous force data on the pedal axis was recorded and used to calculate the BLD. Data were analyzed using a three-way ANOVA with factors of intensity (3% BW, 4% BW, and 5% BW), time during the Wingate (1s – 10s, 11s – 20s, and 21s – 30 s), and position (1 o'clock position and 6 o'clock position). There was an overall BLD of -31.68 ± 21.20% ($p < .001$). The magnitude of the bilateral index (BI) value was significantly affected by the intensity of the Wingate ($p = .006$), and the time period of the Wingate ($p < .001$), but not the position. There were differences in the magnitude of the BLD across intensities and time periods. Overall, a BLD in force exists during maximal arm cycling Wingates and it is affected by fatigue and the movement velocity. Increases in movement velocity decrease the magnitude of the BLD and increased amounts of muscle fatigue likely increase the magnitude of the BLD.

KEYWORDS: Power, fatigue, upper body, velocity

Land Acknowledgement

We respectfully acknowledge the territory in which we gather as the ancestral homelands of the Beothuk, and the island of Newfoundland as the ancestral homelands of the Mi'kmaq and Beothuk. We would also like to recognize the Inuit of Nunatsiavut and NunatuKavut and the Innu of Nitassinan, and their ancestors, as the original people of Labrador. We strive for respectful relationships with all the peoples of this province as we search for collective healing and true reconciliation and honour this beautiful land together.

Acknowledgements

There are many people that contributed to the completion of this thesis. I would first like to thank Dr. Duane Button for his outstanding supervision. Your guidance and honesty have helped me in many ways, both academically and personally, and for that I am very grateful. You were the first person to suggest that I complete my master's degree at Memorial University, and you prevented me from making a costly and ill-advised decision to pursue postgraduate studies outside of the province. I am in a much better position to continue my career and academic journey because of you and for that I will always be indebted to you. I would also like to thank several members of the Human Neurophysiology lab for their respective contributions to this project. I would like to thank Dr. Shahab Alizadeh and the soon to be Dr. Evan Lockyer for their technical knowledge. Without each of you, I would have never advanced beyond the pilot phase of my project. I would also like to thank my friend and colleague Angie Katherin Antolinez Romero for her support throughout the entire data collection process. Despite our contrasting dispositions, I believe that we worked very well together, and we ensured that the data collection phase proceeded in a smooth and timely fashion, even when we encountered an unexplainable vanishing SD card. Lastly, I would like to thank my girlfriend Ofure, each of my classmates & instructors, and the many different people that I had the chance to meet during my master's degree. I am a better person than I was two years ago and for that I thank all of you. I learned so much and I feel that I gained many new friends that I hope to retain in the future. To conclude, it is impossible to include every single person that helped me over the last two years in this short acknowledgement. If I did happen to omit anybody who helped me along the way, your contributions are still very much appreciated. I look forward to taking my next step in my life and I will forever be grateful for my time in this faculty.

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List of Abbreviations

BLD – Bilateral deficit

%BW – Percentage of body weight

BI – Bilateral index

TMW – Total mechanical work

PP – Peak power

EMG - Electromyography

RPM – Rotations per minute

Hz – Hertz, cycles per second

W – Watts

PAR-Q+ - Physical Activity Readiness Questionnaire+

BLF – Bilateral facilitation

J - Joules

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1.0 Introduction

1.1 Overview

The bilateral deficit phenomenon (BLD) is a motor phenomenon characterized by a reduction in performance during a bilateral motor task compared to the performance during the unilateral version of the same motor task. The BLD phenomenon is a topic of interest in exercise neurophysiology because it may represent a limitation in the nervous system (Jakobi & Chilibeck, 2001). A BLD has been found in several motor outputs and contraction types in the upper and the lower limbs with varying magnitudes (Jakobi & Chilibeck, 2001; Škarabot et al., 2016). Numerous studies have assessed the BLD phenomenon during maximal isometric contractions (Behm et al., 2003; Buckthorpe et al., 2013; Cornwell et al., 2012; Herbert & Gandevia, 1996; Howard & Enoka, 1991; Kawakami et al., 1998; Koh et al., 1993; Oda & Moritani, 1995), and maximal dynamic contractions (Cresswell & Ovendal, 2002; Dickin & Too, 2006; Janzen et al., 2006; Magnus & Farthing, 2008; Owings & Grabiner, 1998), however, only one study has been conducted using a maximal cyclical movement (Dunstheimer et al., 2001). This is likely because there is less variability during isometric contractions and controlled dynamic contractions and it is easier to determine the potential mechanisms underlying the BLD (Jakobi & Chilibeck, 2001). While these types of motor outputs may be better for determining the potential mechanisms underlying the BLD phenomenon, the external validity of these studies is suboptimal since many human movements involve the simultaneous use of multiple joints and muscles with changing joint angles and contraction velocities.

It has been stated that the BLD phenomenon appears to be limited to twin-synchronous movements, e.g., simultaneous flexion, but not simultaneous flexion and extension (Ohtsuki, 1983; Škarabot et al., 2016), however, there is little evidence to support this claim. No one has attempted to determine if there is a BLD during asynchronous arm cycling, a motor output that involves simultaneous elbow flexion and extension. This study will attempt to quantify if there is a bilateral deficit in force during arm cycling. This will help to increase the knowledge of the BLD phenomenon during cyclical movement, and it will improve our understanding of how the BLD phenomenon manifests during complex, asynchronous motor outputs.

1.2 Purposes

The purposes of this study are to quantify the bilateral deficit in force during maximal arm cycling Wingates and to determine if the magnitude is affected by the intensity, measured by the percentage of the participant's body weight (% BW), the time period of the Wingate (1s – 10s, 11s – 20s, 21s – 30s), or the position during arm cycling (1 o'clock position vs. 6 o'clock position).

1.3 Research Hypotheses

It is hypothesized that:

1. There will be a significant bilateral deficit in force during arm cycling.
2. The magnitude of the bilateral deficit in force will be affected by the intensity, the time period of the Wingate, and the position.

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2.0 Review of Literature

2.1 Introduction

The bilateral deficit phenomenon is a complex motor phenomenon characterized by a reduction in performance during a bilateral motor task when compared to unilateral performance during the same motor task.

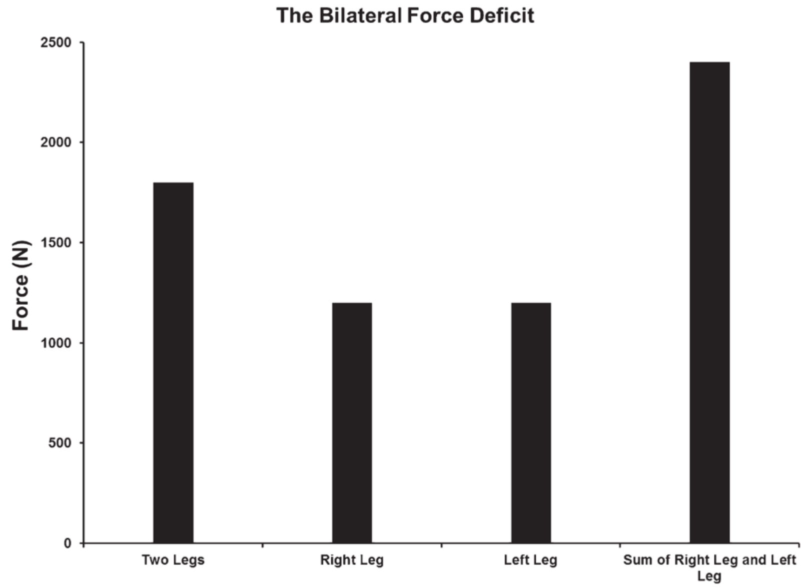

Figure 1. A theoretical representation of the BLD phenomenon during unilateral and bilateral leg press (Nijem & Galpin, 2014). Notice how the sum of force from the right leg and the left leg during unilateral leg press is greater than the force from both legs during bilateral leg press. This is an example of a BLD in force.

A BLD has been found in many different motor outputs and contraction types in the upper and lower limbs with varying magnitudes (Jakobi & Chilibeck, 2001; Škarabot et al., 2016). Numerous studies have explored the BLD phenomenon during isometric contractions (Behm et al., 2003; Buckthorpe et al., 2013; Cornwell et al., 2012; Herbert & Gandevia, 1996; Howard & Enoka, 1991; Kawakami et al., 1998; Koh et al., 1993; Oda & Moritani, 1995), and dynamic contractions (Cresswell & Ovendal, 2002; Dickin & Too, 2006; Janzen et al., 2006; Magnus & Farthing, 2008; Owings & Grabiner, 1998), however, there is only one study that has explored the BLD phenomenon during a cyclical movement (Dunstheimer et al., 2001). Very little is known about the presence, magnitude, and potential mechanisms of the BLD phenomenon during cyclical movements. No studies have determined if there is a BLD in force during a cyclical movement, and no studies have assessed the BLD phenomenon using an upper body cyclical movement. Further exploration of the BLD phenomenon during cyclical movements may lend insight into how complex bilateral and unilateral locomotor type movements are produced and it may help to enhance neurorehabilitation techniques.

2.2 Bilateral Deficit

2.2.1 Bilateral Deficit Definition.

There is no consensus definition for the BLD phenomenon and there are several problematic inconsistencies with past definitions for the BLD phenomenon. Most researchers tend to define the BLD phenomenon as a reduction in force during a maximal simultaneous bilateral motor output compared to the sum of the maximal unilateral force from each limb during the same motor output. However, the BLD phenomenon has also been defined as a "reduction in performance during synchronous bilateral movements when compared to the sum of identical unilateral movements" (Buckthorpe et al., 2013). Within these two definitions, there are discrepancies that can cause confusion. Is the phenomenon solely based on measurements of force, or can it include other measures of performance? Is the phenomenon limited to twin synchronous motor outputs with homonymous limbs, or can it include non-homonymous limbs and asynchronous motor outputs like cycling? And lastly, does the BLD phenomenon only include maximal efforts, or can it include sub-maximal efforts? Depending on how one defines the BLD phenomenon, many studies that claim to be assessing the BLD phenomenon may be measuring a different phenomenon. Several studies have assessed the presence of a BLD using measures of performance such as reaction time, total mechanical work, and ground contact time (Bishop et al., 2019; Dunstheimer et al., 2001; Vieluf et al., 2017). The question is, do these measures constitute a BLD or are they representative of a different phenomenon? It is imperative before starting, to define the BLD phenomenon and to clearly state what measures are included under the definition.

For this literature review, a combination of the Buckthorpe et al. (2013), the Škarabot et al (2016), and the Jakobi and Chilibeck (2001) definitions will be used. This definition will be inclusive of studies that assess the BLD phenomenon using several performance measures, not just force. The definition for the BLD phenomenon that will be used is "a reduction in performance during a bilateral motor task when compared to the performance during the same motor task unilaterally". In the future, a clear, consensus definition of the BLD phenomenon must be created. This will help to eliminate the ambiguity and it will make further study of the BLD phenomenon easier. For now, authors should specify and differentiate what variables they are assessing the BLD for (force, power, rate of force development, etc.) to ensure that they are clearly communicating their research findings and intentions.

2.2.2 What is the Bilateral Deficit Phenomenon?

The BLD phenomenon is typically calculated using the bilateral index (BI) equation below (Howard & Enoka, 1991).

$$BI\ (\%) = \left(100 \times \frac{Bilateral\ performance}{Right\ unilateral\ performance + Left\ unilateral\ performance}\right) - 100$$

The BLD phenomenon was first discovered by Henry and Smith (1961) when they found a reduction in grip strength in the dominant arm during simultaneous maximal bilateral hand grip contraction when compared to the grip strength from the dominant arm during a maximal unilateral hand grip contraction.

TABLE 1.—STRENGTH IN KILOGRAMS

Tests		Dominant		Nondominant	
		Single	Simultaneous	Single	Simultaneous
Test 1	M	62.9	62.2	47.7	48.0
	σ	9.28	8.82	5.86	6.32
Test 2	M	64.1	61.1	47.8	48.1
	σ	8.16	8.56	6.46	7.19
Average		63.5	61.7	47.8	48.1
Simultaneous Minus Single			—1.8		+0.3

Table 1. The first demonstration of the BLD phenomenon from Henry and Smith (1961). Dominant hand grip strength was greater in the unilateral condition when compared to the simultaneous bilateral condition (Henry & Smith, 1961).

Since this initial finding in 1961, many further studies have been conducted to determine if the BLD phenomenon exists in different motor outputs and to determine the potential mechanisms underlying the phenomenon. To date, a BLD has been shown to exist in many upper-body and lower-body motor outputs across multiple contraction types, joint angles, and movement velocities (Jakobi & Chilibeck, 2001; Škarabot et al., 2016). However, the magnitude of the BLD varies considerably across studies and it is an inconsistent phenomenon (Škarabot et al., 2016). The BLD phenomenon is also plastic and it can be increased or decreased with specific unilateral or bilateral training (Janzen et al., 2006; Secher, 1975; Taniguchi, 1997, 1998). The mechanisms underlying the bilateral deficit phenomenon are not clearly understood, however, several neural, physiological, biomechanical, and task-related factors have been proposed to contribute to the existence of the phenomenon (Škarabot et al., 2016). It is likely that the phenomenon exists due to a combination of these factors, however, the amount of influence from each factor during different motor outputs is unclear. More research is required to determine the connection between the BLD phenomenon and athletic performance, movement impairment, or injury. Future work needs to explore more complex, dynamic motor outputs that are more like human movements that we see in our everyday lives. This will improve our understanding of the production of human movement and how we can enhance it in rehabilitation and performance settings.

2.2.3 Mechanisms of the Bilateral Deficit Phenomenon

Since the initial discovery of the BLD phenomenon, researchers have tried to determine the mechanisms that are responsible for the phenomenon. Despite many attempts, the exact mechanisms underlying are still unknown (Škarabot et al., 2016). The BLD phenomenon is likely multifactorial and it is probable that the mechanisms underlying the bilateral deficit phenomenon differ for different types of movements (ex. isometric vs. dynamic vs. ballistic) (Jakobi & Chilibeck, 2001; Škarabot et al., 2016).

2.2.3.1 Biomechanical Mechanisms.

2.2.3.1.1 Counterbalances and Body Positioning. The ability to use counterbalances (i.e., when a dynamometer allows for trunk torsion to the contralateral side of the limb) and the dynamometer configuration has been shown to affect the magnitude and presence of a BLD (Simoneau-Buessinger et al., 2015; Škarabot et al., 2016). The ability to generate trunk torsion can increase the net torque that is produced during unilateral conditions which can lead to a BLD (Škarabot et al., 2016). A study from Simoneau-Buessinger et al. (2015) showed bilateral facilitation with a dynamometer configuration that permitted horizontal movement of the lower limb but a BLD with a dynamometer configuration that did not permit any horizontal movement of the lower limb. These results demonstrate that the BLD phenomenon may be partially due to the setup of the dynamometer and the ability or inability to use counterbalances (Simoneau-Buessinger et al., 2015; Škarabot et al., 2016). It is imperative to consider the potential effects of your experimental setup and the participant's body positioning on the magnitude and presence of the BLD. One must be able to quantify or specify how they controlled the influence of counterbalances and body positioning to ensure that they are not potentially responsible for a BLD.

2.2.3.1.2 Force-Velocity Relationship. The relationship between force and velocity in human skeletal muscles is generally, inversely related, meaning that as velocity increases, the force tends to decrease and vice versa (Jaric, 2015). It is unclear exactly how the force-velocity relationship affects the magnitude and the presence of the BLD phenomenon. Škarabot et al. (2016) have stated that as the contraction velocity increases, the magnitude of the BLD tends to increase as well. However, the existing evidence regarding the force-velocity relationship and its effect on the magnitude of the BLD phenomenon is equivocal. There are conflicting results throughout much of the literature that makes the establishment of a clear relationship between movement velocity and the magnitude of the BLD difficult.

Studies from Vandervoort et al. (1984) and Dickin and Too (2006) showed that when contraction velocity was increased, there was a corresponding increase in the magnitude of the BLD (Dickin & Too, 2006; Vandervoort et al., 1984). However, a study from Brown et al. (1994), found directly opposing results that showed that the magnitude of the BLD decreased as the movement velocity increased. Upon further evaluation, there does not appear to be any clear reasons for the differing results in the Brown et al. (1994) study. Each of the three studies utilized similar motor outputs and had similar participant populations.

A study by Koh et al. (1993) found that the magnitude of the BLD was greater during rapid isometric contractions when compared to slower ramp isometric contractions. Buckthorpe et al. (2013), also found a BLD in rate of force development from 50-100 ms during explosive knee extension. These results would support the notion that as movement velocity increases so too does the magnitude of the BLD. However, several other studies have shown that BLD values at low movement velocities can be equally as high, or higher (Dickin & Too, 2006; Kuruganti & Seaman, 2006), than BLD values at greater movement velocities during dynamic contractions (Botton et al., 2013; Taniguchi, 1997, 1998).

Like much of the literature surrounding the BLD phenomenon, the relationship between movement velocity and the magnitude of the BLD is variable and inconsistent. A clear relationship between movement velocity and the magnitude of the BLD does not exist. There are studies that show that an increase in movement velocity tends to increase the magnitude of the BLD (Dickin & Too, 2006; Koh et al., 1993; Vandervoort et al., 1984), however, these findings are not unanimous (Brown et al., 1994; Kuruganti & Seaman, 2006; Škarabot et al., 2016). More directed research needs to be completed to conclusively determine the effects of movement velocity on the BLD phenomenon during different motor outputs and contraction types.

2.2.3.2 Neurophysiological Mechanisms.

2.2.3.2.1 Interhemispheric Interactions. When performing bilateral and unilateral movements in the upper limb, there is a complex balance of interhemispheric facilitation and interhemispheric inhibition between the two primary motor cortices (Fling & Seidler, 2012; MacDonald et al., 2021). It is possible that changes in the amount of interhemispheric inhibition may be a mechanism underlying the BLD phenomenon (Škarabot et al., 2016). Interhemispheric inhibition is a neural mechanism that inhibits one cerebral hemisphere in response to the activation of the other cerebral hemisphere (Beaulé et al., 2012; Iwata et al., 2016). It has been stated that humans have a tendency to perform symmetrical contractions of homologous muscles, also called voluntary mirror movements (Beaulé et al., 2012; Cincotta et al., 2004; Grefkes et al., 2008). In order to minimize these voluntary mirror movements and perform strictly unilateral movements, there is a 'non-mirroring' process that occurs to suppress motor activation of the mirror hand (Beaulé et al., 2012; Leocani et al., 2000). This is achieved through complex interhemispheric communication and modulation of interhemispheric inhibition between cortical (i.e., dorsal premotor cortex, supplementary motor area) and subcortical (i.e., basal ganglia) areas (Beaulé et al., 2012).

Studies from Oda and Moritani (1995, 1996) have shown that symmetrical movement-related cortical potentials of lower amplitude, compared to those seen during unilateral contractions, are present in both motor cortices during bilateral contractions. It was suggested that this weaker, symmetrical drive, may be due to interhemispheric inhibition of the primary motor cortices during bilateral motor outputs (Oda & Moritani, 1996; Škarabot et al., 2016). Perez et al. (2014) provided further support for this idea by showing that the depth and area of the ipsilateral silent period, a measure of interhemispheric inhibition, was increased during bilateral motor outputs compared to unilateral motor outputs. This finding matched other studies which showed that interhemispheric inhibition is greater during bilateral contractions compared to unilateral contractions (Soteropoulos & Perez, 2011; Yedimenko & Perez, 2010). It seems that interhemispheric inhibition is a potential mechanism for the BLD phenomenon. Multiple studies have shown that there is greater interhemispheric inhibition to the primary motor cortex during bilateral contractions compared to unilateral contractions, thus, it is reasonable to believe that this may be a factor responsible for the BLD phenomenon. More research using neurophysiological techniques such as electroencephalograms, transcranial magnetic stimulation, and EMG is worthwhile to further explore the neural mechanisms underlying the BLD phenomenon.

2.2.4 The Bilateral Deficit Phenomenon During Cycle Ergometry.

Very little is known about the magnitude, presence, and potential mechanisms of the bilateral deficit phenomenon during cyclical movements. There is only one study that has assessed the BLD phenomenon during a cyclical movement (Dunstheimer et al., 2001). Most work assessing the BLD phenomenon has used tightly controlled isometric and dynamic contractions. This is likely due to the lower amount of variability that is present during these motor outputs and the greater ease in determining the potential mechanisms underlying a BLD (Jakobi & Chilibeck, 2001). It has been stated that the BLD phenomenon appears to be limited to twin-synchronous movements, but not simultaneous flexion and extension which can be seen during asynchronous cycling movements (Ohtsuki, 1983; Škarabot et al., 2016). However, there is limited evidence to support this claim. More research is required to better understand how the BLD phenomenon manifests during cyclical motor outputs and what potential mechanisms may be responsible for a BLD or lack thereof.

2.2.4.1 Summary. As stated before, there is only one study assessing the BLD phenomenon during cyclical movement, therefore, this summary of the literature is very limited in its scale. While the lack of research limits the ability to make conclusions about the magnitude and presence of the BLD phenomenon during cyclical movements, there is ample room for expansion of the research on this topic and the ability to make novel findings.

Dunstheimer et al. (2001) explored the bilateral deficit during maximal 30-second leg cycling Wingate sprints in males and females at varying stages of pubertal maturity. Two unilateral Wingate tests were performed in a random order followed by one bilateral Wingate test. There were 20 minutes of rest between each Wingate to minimize the effects of fatigue. In their study, they found a significant, almost unanimous, BLD in total mechanical work (TMW) and peak power (PP). The magnitude of the BLD ranged from ~7% to ~20% and it tended to be larger in females than in males. This study was the first to show a BLD during an alternating, asynchronous movement which had not previously been observed in other studies (Kawakami et al., 1998; Ohtsuki, 1983). Unfortunately, there does not appear to be any follow-up studies from the initial Dunstheimer et al. (2001) study, thus, one cannot determine the replicability of the results or the transferability of the BLD in PP and TMW to force.

There does appear to be a BLD in TMW and PP during maximal cyclical movement in the lower body. Unfortunately, these results cannot be extrapolated to the upper body, and it is unclear if the same results would be observed under different experimental conditions (i.e., resistance levels, participant populations, etc.), variables (i.e., force, mean power, etc.), or movements.

2.2.4.2 Future Research. The first and most important direction for future research is to increase the number of studies that assess the BLD phenomenon during cyclical movements. Currently, there are not enough studies to make definitive statements about the magnitude or the mechanisms of the BLD phenomenon during cyclical movement. More studies need to be performed to determine if the results that have already been shown are replicable and to identify the potential mechanisms that may be responsible for a BLD. Studies using a similar design to Dunstheimer et al. (2001) with modifications to the experimental conditions (i.e., upper limb vs. lower limb, different resistance levels, different participant populations, etc.) need to be completed to increase the research base on the topic. Once more studies have been conducted, comparisons between experimental conditions could then be made and further explorations of the potential mechanisms underlying the BLD phenomenon will be possible.

Another important consideration for future research on the BLD phenomenon during cyclical movement is the implementation of more advanced data collection techniques. In the Dunstheimer et al. (2001) study, the only data that was generated was the performance data from the cycle ergometer. They did not record any electromyographic (EMG) activity from the leg muscles, nor did they perform any kinetic or kinematic analysis. Due to this lack of data, their speculation of the potential mechanisms in the discussion section was limited. Future studies should strive to perform a kinematic, kinetic, and neurophysiological analysis of a movement to generate a well-rounded picture of the BLD phenomenon and its potential mechanisms.

2.2.5 Conclusion

The BLD phenomenon is complex, inconsistent, highly variable, and subject to training adaptations (Jakobi & Chilibeck, 2001; Janzen et al., 2006; Secher, 1975; Škarabot et al., 2016; Taniguchi, 1997, 1998). While there is some ambiguity surrounding its definition, the BLD phenomenon has been extensively investigated to determine its existence in different motor outputs and to identify what mechanisms are responsible for the deficit. Despite the numerous studies that have demonstrated the existence of a BLD, the exact mechanisms that are responsible for the phenomenon remain unclear (Škarabot et al., 2016). It is likely that the BLD phenomenon is due to a combination of neural and biomechanical factors, however, it is uncertain to what extent each factor is responsible for the BLD during different types of motor outputs (Jakobi & Chilibeck, 2001; Škarabot et al., 2016). More research into the mechanisms of the BLD phenomenon is required to determine if the phenomenon is primarily neural or if it is due to a combination of neural, biomechanical, and task-related factors.

With regards to cyclical movement, very little is known about the BLD phenomenon and there is potential for a vast expansion of the research on the topic. More research is required to conclusively determine the mechanisms underlying the BLD phenomenon during different motor outputs. Implementing the use of neurophysiology techniques in conjunction with kinetic and kinematic analysis would enable a well-rounded investigation into the potential mechanisms underlying the BLD phenomenon. Future studies should aim to study the BLD phenomenon from multiple perspectives as the phenomenon is complex and multifactorial.

2.3.1 What is Arm Cycling?

Arm cycling is a rhythmic, cyclical, dynamic motor output that is often performed in research and neurorehabilitation settings to help restore gait, improve our understanding of fatigue during intense motor outputs, and to better understand the neural control of locomotor type movements (Chaytor et al., 2020; Lockyer et al., 2021; Pearcey et al., 2016; Power et al., 2018). Arm cycling is regularly used in our lab as an upper-body model of locomotion to assess state- and task-dependent changes in neural excitability during dynamic movements and to assess the effects of intense exercise on the nervous system (Klarner & Zehr, 2018; Lockyer et al., 2021; Pearcey et al., 2016; Power et al., 2018). Arm cycling is a good model of locomotion because it is likely partially controlled by central pattern generators in the spinal cord, similar to human gait (Klarner & Zehr, 2018; Lockyer et al., 2021; Power et al., 2018). Arm cycling training possesses significant value in rehabilitation as it has been shown to improve walking performance and neurophysiological integrity in stroke (Kaupp et al., 2018; Zehr et al., 2016) and it has also been shown to increase physical fitness and functional independence in wheelchair users (Glaser, 1989). Due to the similarities in neural control between arm cycling and human gait, its easy accessibility, and its demonstrated effectiveness in rehabilitation settings, arm cycling is a very useful and relevant motor output for researchers in the field of neurophysiology and rehabilitation professionals. Studying arm cycling can improve our understanding of the neural mechanisms of fatigue, and the neural control of human gait, and it can help to create more effective rehabilitation practices for people who have neurological injuries or diseases.

2.3.2 Arm Cycling Wingates as a Model for the Bilateral Deficit Phenomenon.

No one has explored the BLD phenomenon during arm cycling and there is only one study that has explored the BLD phenomenon during cyclical movement (Dunstheimer et al., 2001). It has yet to be determined if a BLD exists during arm cycling and the potential mechanisms underlying a BLD during arm cycling are unknown. Our lab has performed many studies utilizing arm cycling to improve our understanding of the neural control of complex, cyclical movements, the neural mechanisms of fatigue, and the effects of intense exercise on the nervous system (Chaytor et al., 2020; Lockyer et al., 2020, 2021, 2023; Nippard et al., 2020; Pearcey et al., 2016; Power et al., 2018; Spence et al., 2016). From these numerous studies, many questions have arisen surrounding the neural control and production of complex cyclical movements. Using the technology that we possess in our lab, a comprehensive neurophysiological, kinetic, and kinematic analysis of the BLD phenomenon during arm cycling is possible. Not only will this add to the considerable literature surrounding the BLD phenomenon, but it will also contribute to the literature surrounding the neural control of arm cycling. Utilizing a similar study design to Dunstheimer et al. (2001), a maximal arm cycling study exploring the BLD phenomenon serves multiple purposes. Firstly, it will help to determine if a BLD in force exists during maximal arm cycling, and it will also help to improve our understanding of the patterns of force production during maximal bilateral and unilateral arm cycling. Secondly, it will help to improve our understanding of how fatigue throughout an intense motor output affects the presence and magnitude of the BLD phenomenon. And lastly, it will help to improve our understanding of the mechanisms of the BLD phenomenon and provide an in-depth exploration of the neuromechanical factors underlying the BLD phenomenon.

Overall, there are several reasons why maximal arm cycling Wingates are a good model for exploring the BLD phenomenon. Firstly, it is a vastly under researched area with no studies directly exploring the topic. Thus, there is ample room for novel discoveries to be made. Additionally, our lab has extensive experience studying these types of motor outputs and can perform an in-depth study encompassing neurophysiology, kinetic, and kinematic techniques to explore this topic. This would improve our understanding of the arm cycling movement and fuel future studies within our lab. There are still many questions surrounding the control of complex, cyclical motor outputs. A study of this nature will improve our understanding of the production of cyclical movement while also strengthening our knowledge of the BLD phenomenon.

2.3.3 How to Classify Arm Cycling.

During arm cycling, there are changes in reflex responses, muscle activation patterns, kinematics, kinetics, and corticospinal excitability depending on the workload, the direction of the movement, the phase of the movement, and the muscles that are being assessed (Chaytor et al., 2020; Klimstra et al., 2011; Lockyer et al., 2021; Nippard et al., 2020; Spence et al., 2016; Zehr et al., 2003; Zehr & Chua, 2000; Zehr & Kido, 2001). Due to the dynamic nature of arm cycling, researchers must be able to control and monitor the various characteristics of the arm cycling movement to ensure that their studies are replicable.

Arm cycling can be characterized in many ways. It can be characterized by the cadence, measured in rotations per minute (RPM) or cycles per second (Hz), the power output in watts (W), the forearm position (pronated grip vs. supinated grip vs. neutral grip), the synchronicity of the movement, asynchronous, (both arms moving through the same phase simultaneously) versus synchronous (each arm moving through alternating phases), the direction (forward vs. backward) and whole-body position (seated versus supine, etc.) (Chaytor et al., 2020; Smith et al., 2008b; Zehr & Chua, 2000). It is imperative to measure and record each of these characteristics because they can modulate neural responses and they can greatly affect the results of a study if they are not accounted for.

2.3.3.1 Arm Cycling Positions. To compare and standardize the results from arm cycling studies, the position of the arm crank must be monitored. In our lab, the crank position during arm cycling is made relative to a clock face as shown below (Nippard et al., 2020).

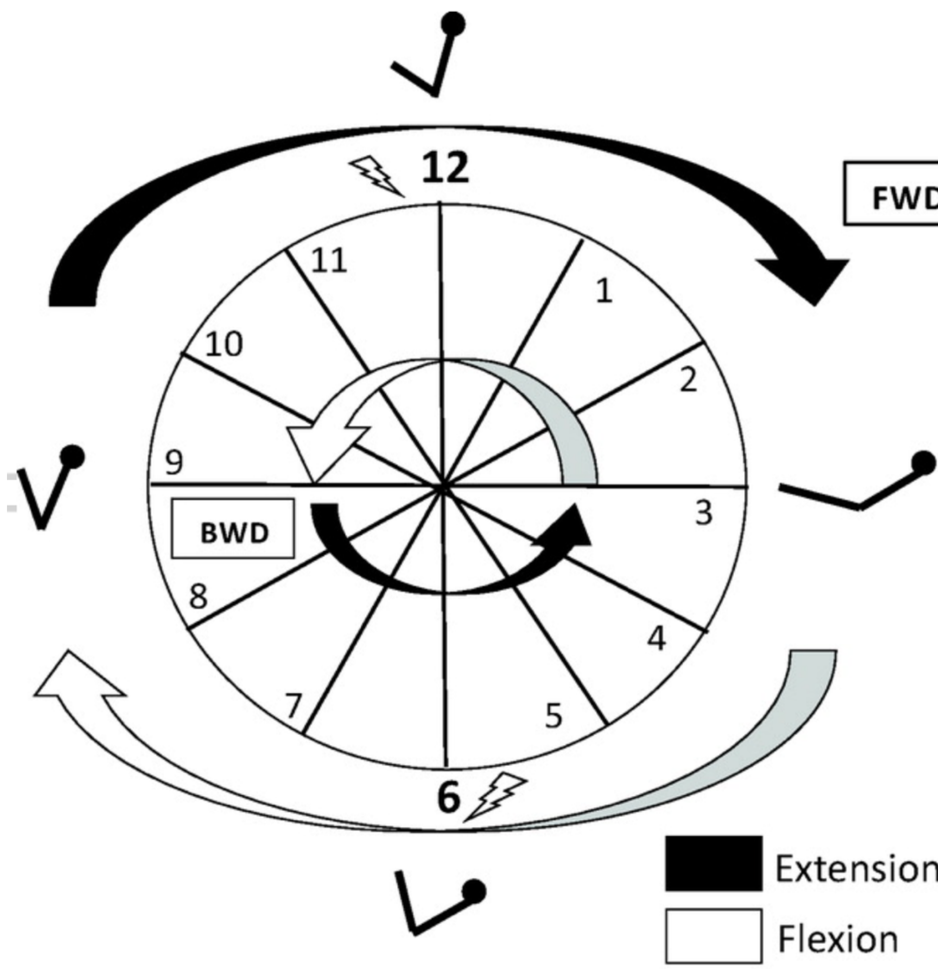

Figure 2. Arm cycling positions relative to a clock (Nippard et al., 2020).

When the arm crank is at the top of the cycle, this is referred to as the 12 o'clock position and when the arm crank is at the bottom of the cycle, this is referred to as the 6 o'clock position. This positioning system helps to ensure the consistent delivery of stimulations and consistent measurements that can be compared between studies. This positioning system will be used throughout the literature review when referencing arm cycling studies.

2.3.3.2 Forward Arm Cycling Phases. The forward arm cycling movement can be roughly divided into two phases, the flexion phase, and the extension phase. The flexion phase corresponds to when the arm crank is between the 3 o'clock position and the 9 o'clock position (Chaytor et al., 2020; Nippard et al., 2020). During this phase, the arm crank is being "pulled" towards the participant and the elbow flexor muscles are most active. The extension phase of arm cycling occurs from approximately the 9 o'clock position to the 3 o'clock position (Chaytor et al., 2020; Nippard et al., 2020). During this phase, the arm crank is being "pushed" away from the participant and the elbow extensor muscles are most active. During asynchronous arm cycling, the flexion phase in one arm occurs while the other arm is in the extension phase. However, during synchronous arm cycling, the phases occur for both arms simultaneously. It is important to note that during backward arm cycling, the positions for each phase are the opposite of what is seen during forward arm cycling.

2.3.4 Upper Limb Movement Analysis of Bilateral Arm Cycling.

2.3.4.1 Muscle Activation. There are phasic, alternating, and reciprocal activation patterns between flexor and extensor muscles at the wrist, elbow, and shoulder during arm cycling (Chaytor et al., 2020; Klimstra et al., 2011; Zehr et al., 2003; Zehr & Chua, 2000; Zehr & Kido, 2001). Muscle activation patterns during arm cycling are phase-dependent and intensity-dependent. This means that muscle activation patterns vary at different intensities and during the different phases of the arm cycling movement (Chaytor et al., 2020; Klimstra et al., 2011; Zehr et al., 2003; Zehr & Chua, 2000; Zehr & Kido, 2001). It has been shown that there is a linear relationship between the amount of EMG activity and the power output, which means that as the power output during arm cycling increases, the amount of EMG activity tends to increase as well (Chaytor et al., 2020). This is due to the greater muscle force demands during higher power outputs. This section outlines the general muscle activation patterns that can be seen during arm cycling; however, it does not represent exact muscle activation patterns during different intensities, cadences, power outputs, and various other conditions.

2.3.4.1.1 Biceps Brachii. The biceps brachii muscle is most active during the "pulling" or the flexion phase of arm cycling as it is one of the main elbow flexor muscles during the arm cycling movement (Chaytor et al., 2020; Klimstra et al., 2011). Biceps brachii muscle activation begins to increase from a minimal level of activation at around the 3 o'clock position until it reaches its peak levels of muscle activation at around the 5 o'clock or 6 o'clock position (Chaytor et al., 2020; Klimstra et al., 2011). After the point of peak activation at the 5 o'clock position, muscle activation decreases until the 8 o'clock position where it remains minimally active until the next flexion phase (Chaytor et al., 2020; Klimstra et al., 2011).

2.3.4.1.2 Triceps Brachii. The triceps brachii muscle displays a biphasic pattern of muscle activation during arm cycling which means that it has two distinct phases of muscle activation during the movement (Chaytor et al., 2020). This differs from the biceps brachii muscle which is monophasic and displays only one main phase of muscle activation (Chaytor et al., 2020; Klimstra et al., 2011). The highest levels of muscle activation for the triceps brachii muscle can be seen in the "pushing" or the extension phase as it is one of the main elbow extensors during the arm cycling movement (Chaytor et al., 2020; Klimstra et al., 2011). During the extension phase, there is a rapid increase in activation from the 9 o'clock position to the point of peak activation at the 11 o'clock or 12 o'clock position followed by a rapid decrease in activation from the 12 o'clock position to the 3 o'clock position (Chaytor et al., 2020; Klimstra et al., 2011). The second phase of activation for the triceps brachii muscle occurs from approximately the 3 o'clock position to the 7 o'clock position. The muscle activation during this phase follows the same shape as the muscle activation during the main phase, however, there is a lower magnitude of activation (Chaytor et al., 2020; Klimstra et al., 2011). It is believed that during this phase, the triceps brachii acts as a stabilizer for the hand and the elbow (Chaytor et al., 2020). However, this activation may also be due to unnecessary co-contraction due to unfamiliarity with the arm cycling movement (Chaytor et al., 2020).

2.3.4.1.3 Deltoid. The deltoid muscle can be divided into three separate parts, the anterior deltoid, the medial deltoid, and the posterior deltoid (Elzanie & Varacallo, 2023). Each distinct part of the deltoid displays different muscle activation patterns during arm cycling which is likely due to their different functions during the arm cycling movement (Elzanie & Varacallo, 2023; Klimstra et al., 2011).

The anterior deltoid has a monophasic activation pattern as it is highly active during the extension phase to help push the crank forward and minimally active during the rest of the cycle (Chaytor et al., 2020; Klimstra et al., 2011). There is a rapid increase in anterior deltoid activation from the 7 o'clock position until the peak activation at the 10 o'clock position followed by a rapid decrease in activation until the 3 o'clock position (Chaytor et al., 2020). Anterior deltoid activation remains minimal from the 3 o'clock position to the 7 o'clock position until the next extension phase (Chaytor et al., 2020).

The medial deltoid maintains a consistent amount of muscle activation throughout the arm cycling movement likely to help stabilize the shoulder joint (Elzanie & Varacallo, 2023; Klimstra et al., 2011). Medial deltoid muscle activation increases from a low level of activation at the 2 o'clock position until roughly the 5 o'clock position and then remains consistent at a moderate level of activation until around the 1 o'clock position (Klimstra et al., 2011).

The posterior deltoid muscle appears to display a biphasic muscle activation pattern (Chaytor et al., 2020; Klimstra et al., 2011). The two distinct phases of muscle activation are from the 2 o'clock position to the 7 o'clock position, and from the 8 o'clock position to the 2 o'clock position (Klimstra et al., 2011). In both phases, there is a steady increase in activation followed by a steady decrease in activation (Klimstra et al., 2011). The first phase has slightly higher levels of muscle activation than the second phase of activation (Klimstra et al., 2011). It is likely that the posterior deltoid muscle acts as a stabilizer of the shoulder joint similar to the medial deltoid muscle in both of these phases (Elzanie & Varacallo, 2023).

2.3.4.1.4 Forearm Flexors and Extensors. There are many muscles in the forearm that help to stabilize the wrist joint and transfer the forces that were generated in distal upper limb muscles into the crank. Two forearm muscles that have been evaluated are the flexor carpi radialis and the extensor carpi radialis (Chaytor et al., 2020; Klimstra et al., 2011). This is likely due to their superficiality and their important role in wrist flexion and extension (Chaudhry et al., 2023).

The flexor carpi radialis muscle maintains a consistently high level of activation throughout the whole cycle and there appears to be a biphasic activation pattern (Chaytor et al., 2020; Klimstra et al., 2011). The two distinct phases of muscle activation are from the 2 o'clock position to the 5 o'clock position, and from the 8 o'clock position to the 2 o'clock position

(Klimstra et al., 2011). In both phases, there is a steady increase in activation followed by a steady decrease in activation (Klimstra et al., 2011). During these phases, it is likely that the flexor carpi radialis muscle is stabilizing the wrist joint and assisting with wrist flexion.

The extensor carpi radialis muscle displays a biphasic activation pattern in Klimstra et al. (2011) but a monophasic activation pattern in Chaytor et al. (2020). In both studies, the extensor carpi radialis muscle is active during the elbow flexion phase to help stabilize the wrist (Chaytor et al., 2020; Klimstra et al., 2011). However, during the Klimstra et al. (2011) study, there was an additional phase of activation from the 9 o'clock position to the 2 o'clock position that was not seen in the Chaytor et al. (2020) study. This discrepancy may be due to kinematic changes in the upper limbs between the participants in the two studies or differences in the workloads and cadences that were used.

2.3.4.1.5 Core Musculature. Although this section only covers the muscle activation of the upper limbs in-depth, one must not ignore the core musculature and its important role during the arm cycling movement. Core muscles must be active during arm cycling as they help to stabilize the torso and allow for the generation of force and rotational torque with the upper limbs. The ability to better stabilize the core may improve the efficiency of the arm cycling movement and it could lead to improved arm cycling performance. Additionally, the ability to rotate the trunk could help to generate greater force while arm cycling. It is important to acknowledge that changes in force, power, and EMG that may be observed during arm cycling may be partially due to the core musculature and not necessarily just the upper limbs.

2.3.4.2 Kinematics. During arm cycling, there are phasic changes in the kinematics of the trunk, the wrist, the elbow, and the shoulder (Klimstra et al., 2011). The kinematics of arm cycling can be altered by the crank position and length, the direction of the movement, the intensity and the cadence of the movement, and fatigue (Bressel & Heise, 2004; Mason et al., 2021; Mravcsik et al., 2021; Stone et al., 2019). Kinematic changes may lead to changes in muscle activation patterns and changes in the efficiency of the arm cycling movement. It is important to understand the general kinematics of the arm cycling movement since kinematic changes may be a mechanism underlying the results of any arm cycling study.

2.3.4.2.1 Elbow. During arm cycling, the elbow joint moves through cycles of flexion and extension. Starting from the 12 o'clock position, the elbow is at approximately 60° of flexion (Klimstra et al., 2011). The elbow remains roughly at the 60° angle until the 3 o'clock position where the elbow flexion angle begins to increase until it reaches its peak value of approximately 110° at the 7 o'clock position (Klimstra et al., 2011). Then from the 7 o'clock position, the elbow then begins to extend until it reaches the starting angle of 60° at the 12 o'clock position (Klimstra et al., 2011).

2.3.4.2.2 Shoulder. The shoulder joint kinematics are similar to those of the elbow as it also moves through cycles of flexion and extension (Klimstra et al., 2011). Starting at the 12 o'clock position, the shoulder is at approximately 70° of flexion (Klimstra et al., 2011). From the 3 o'clock position to the 6 o'clock position, the shoulder extends quite rapidly from approximately 55° to 25° (Klimstra et al., 2011). Then from the 7 o'clock position, the shoulder begins to flex until it reaches the starting angle of ~70° at the 12 o'clock position (Klimstra et al., 2011). In addition to the cycles of flexion and extension, the shoulder can also demonstrate changes in shoulder abduction and adduction angle when arm cycling (Quittmann et al., 2022). This is likely due to fatigue and compensatory kinematic changes during intense arm cycling bouts.

2.3.4.2.3 Wrist. There are small changes in wrist kinematics during the flexion and extension phases of arm cycling (Klimstra et al., 2011). From the 5 o'clock position until approximately 10 o'clock position there is a small amount of wrist flexion, of approximately 10° (Klimstra et al., 2011). During the remainder of the movement, the wrist remains in an approximately neutral position (Klimstra et al., 2011). There are also slight changes in wrist abduction and adduction throughout the movements, however, these changes are very small in magnitude (Klimstra et al., 2011).

2.3.4.3 Kinetics. There appear to be only 2 studies that have evaluated the kinetics of arm cycling (Klimstra et al., 2011; Smith et al., 2008). Klimstra et al. (2011) evaluated the force at the right handle of the cycle ergometer using a 6-axis force transducer while Smith et al. (2008) evaluated torque production using a professional powermeter with 4 force transducers. The Smith et al. (2008) study was able to display the general pattern of torque production during arm cycling, while the Klimstra et al. (2011) study measured forces at the handle of the cycle ergometer during arm cycling.

2.3.4.3.1 Pattern of Torque Production. When arm cycling, there appears to be a biphasic pattern of torque production with two peak propulsive phases at approximately the 1 o'clock position (16°-30°) and the 6 o'clock position (181°-195°) (Smith et al., 2008). This matches the pattern that is seen during leg cycling (Bertucci et al., 2005).

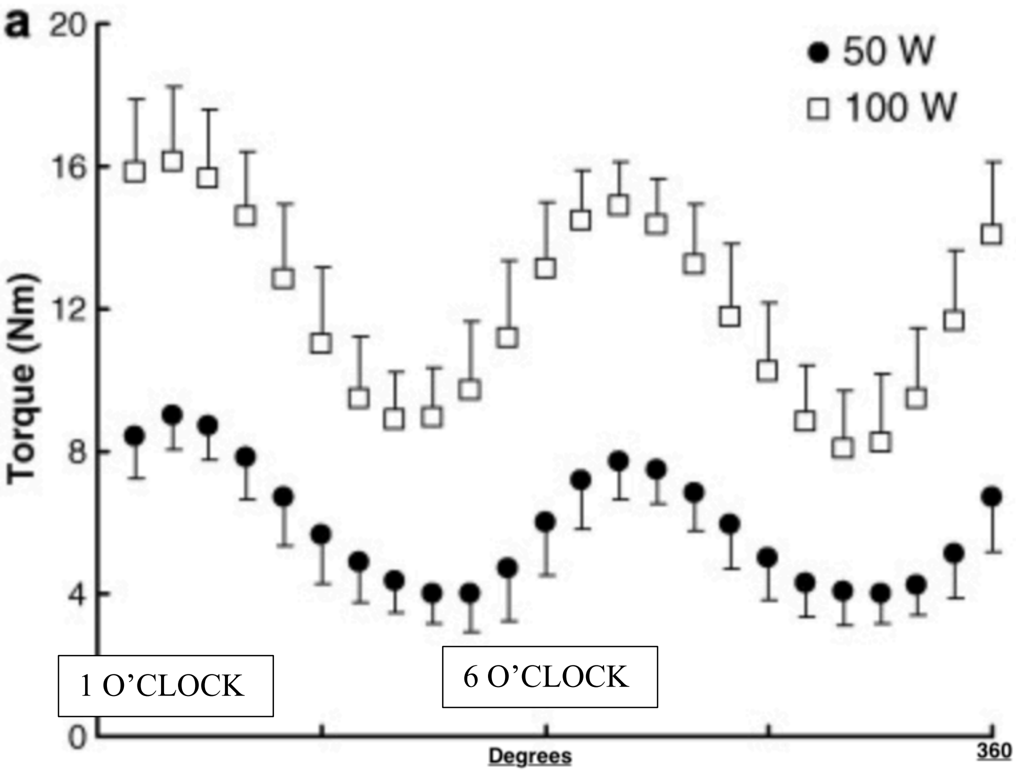

Figure 3. Patterns of torque production during bilateral asynchronous arm cycling at 50 W and 100 W (Smith et al., 2008). Each dot represents a 15° interval. Notice how there are two distinct peaks in torque production at the 1 o'clock position and the 6 o'clock position during the cycle.

After the first peak at approximately the 1 o'clock position, torque production begins to decrease steadily until around the 3 o'clock to 4 o'clock position (~105°) (Smith et al., 2008). This corresponds to the extension phase of arm cycling where the person is pushing the crank forward and extending the elbow. Once the elbow extension phase ends and the elbow flexion phase begins, at around the 5 o'clock position, torque production begins to rise to its second peak at around the 6 o'clock position (Smith et al., 2008). After the second peak propulsive phase, the torque production decreases steadily again until the beginning of the next extension phase at around the 9 o'clock to 10 o'clock position (Smith et al., 2008).

2.3.4.3.2 Forces on the Crank. There are forces in several directions on the hand crank during arm cycling (Klimstra et al., 2011). There is a downward force on the crank throughout the entire cycle to help grip the crank (Klimstra et al., 2011). There is also a backward force on the crank from the 1 o'clock position until the 8 o'clock position and the 10 o'clock position to the 12 o'clock position (Klimstra et al., 2011). This helps to move the crank through the cycle and maintain the person's grip on the crank. Lastly, there are also medial and lateral forces of a small magnitude throughout the entire cycle, likely as a result of gripping the crank (Klimstra et al., 2011).

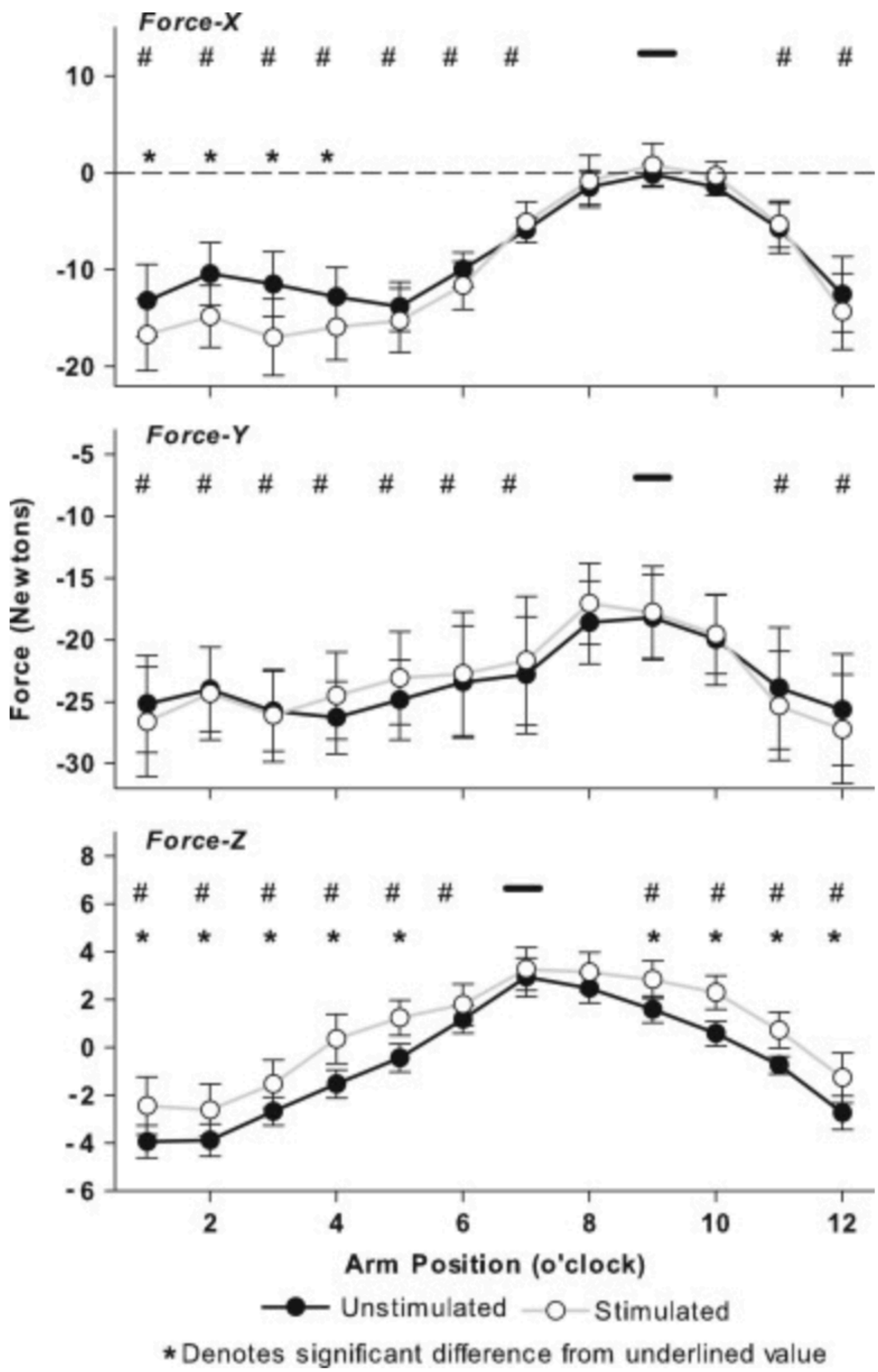

Figure 4. Forces on the crank during arm cycling (Klimstra et al., 2011).

2.3.5 Single-Arm Cycling.

2.3.5.1 What is Single-Arm Cycling? Single-arm cycling, or unilateral arm cycling is arm cycling performed with only one arm actively contributing to the movement of the cranks. This differs from bilateral arm cycling where both arms are actively contributing to the movement of the cranks. There is less research that has assessed unilateral arm cycling and its potential benefits in training and rehabilitation settings, however, unilateral arm cycling can be a more feasible exercise modality than bilateral arm cycling in certain scenarios. For example, a person with hemiparesis or hemiplegia after a stroke or spinal cord injury may not be able to grip a handle with their affected arm and they might not have the strength or the functional capacity to keep their arm in a secure position to perform bilateral arm cycling. Additionally, people who have had limbs amputated would not be able to perform bilateral arm cycling without specific attachments for their amputated limb. In these scenarios, unilateral arm cycling may be the most feasible option for rehabilitation, thus it is important to study the movement and determine the most effective guidelines for exercise prescription.

2.3.5.2 Current Research and Benefits of Single-Arm Cycling. There are few research papers assessing single-arm or unilateral arm cycling. Several papers have assessed the utility of single-arm cycling for fitness testing in people who have had a stroke (Birkett & Edwards, 1998; Oyake et al., 2017). There are also papers comparing the neural responses from bilateral and unilateral arm cycling to determine the similarities and differences in the neural control of each motor output (Loadman & Zehr, 2007; Lockyer et al., 2020). There appears to be only one study comparing the efficacy of unilateral arm cycling training to bilateral arm cycling training in a rehabilitation setting (Renner et al., 2020). More controlled trials comparing bilateral arm cycling training and unilateral arm cycling are required. This will help to determine if and when unilateral or bilateral arm cycling is more advantageous for rehabilitation or performance outcomes.

In the one study that compared unilateral arm cycling training and bilateral arm cycling training, it was shown that unilateral arm cycling improved upper limb function in subacute stroke patients at a similar level to bilateral arm cycling in people with cortical lesions (Renner et al., 2020). However, their results also showed that bilateral arm cycling training was more effective than unilateral training in people with subcortical lesions. It is unclear why the location of the lesion modified the effectiveness of unilateral arm cycling training, however, further exploration into this finding is warranted. Outside of the Renner et al. (2020) study, there does not appear to be any studies directly measuring the effectiveness of unilateral arm cycling as a rehabilitation technique. Thus, one must draw upon studies that have used bilateral arm cycling training to speculate the potential benefits of unilateral arm cycling training.

Bilateral arm cycling training has been shown to be an effective method for improving cardiorespiratory fitness in people with spinal cord injury (Glaser, 1989). Thus, it is reasonable to expect that unilateral arm cycling would have a similar effect on cardiorespiratory fitness levels if the exercise were of a similar intensity and duration. However, the effects on the cardiovascular and nervous system would likely not be the same since there are differences in cardiovascular and neural responses during unilateral and bilateral exercise (Liao et al., 2022; Moreira et al., 2017; Taniguchi, 1997). Currently, there does not appear to be any studies assessing the effectiveness of unilateral arm cycling training for improving cardiorespiratory fitness levels. However, it is likely that unilateral arm cycling training would also improve cardiorespiratory fitness levels, albeit in a different way than bilateral arm cycling training. More research assessing the effects of unilateral arm cycling training on cardiorespiratory fitness levels is warranted to determine the cardiovascular and neural responses that would occur.

Bilateral arm cycling training has also been shown to be an effective tool for improving gait and functional performance in people who have had a stroke (Kaupp et al., 2018). No studies have evaluated the efficacy of unilateral arm cycling as a tool to improve gait, however, there is reason to believe that it would have a similar effect. Unilateral arm cycling and bilateral arm cycling both supress H-reflex amplitude in the lower limbs which indicates that both movements have similar neural control mechanisms and that they are likely both partially controlled within the spinal cord (Loadman & Zehr, 2007). However, it is unclear if the unilateral arm cycling would improve gait in a similar fashion, as gait is a bilateral movement that requires the careful coordination of multiple limbs, unlike single arm cycling. Again, more research is required to determine the effects of unilateral arm cycling on gait post-stroke.

2.3.5.3 Considerations for Single Arm Cycling. There are several considerations that must be made before performing single arm cycling. One of the main considerations is what to do with the inactive arm during the arm cycling movement. Do you place the arm on the other crank to be passively cycled throughout the movement, or do you rest the arm on the body? It has been shown that there are differences in corticospinal and spinal excitability between passive and rest conditions during unilateral arm cycling, thus, inactive arm placement may be an important consideration for rehabilitation purposes (Lockyer et al., 2020). Another important consideration is determining what resistance the person cycles against during unilateral arm cycling. Should you set the resistance to be half of that during bilateral arm cycling, or is there a more precise way to determine the resistance level?

2.3.6 Conclusion.

Arm cycling is a complex, dynamic, motor output that demonstrates varying kinematics, kinetics, reflex responses, and muscle activation patterns (Chaytor et al., 2020; Klimstra et al., 2011; Smith et al., 2008a; Zehr & Chua, 2000). Despite the complexity of the movement, arm cycling is a well-researched topic in the field of neurophysiology, particularly in our lab (Chaytor et al., 2020; Lockyer et al., 2020, 2021, 2023; Nippard et al., 2020; Pearcey et al., 2016; Power et al., 2018; Spence et al., 2016). Due to our lab's familiarity with arm cycling and its great utility for neurorehabilitation, exploring the BLD phenomenon with arm cycling as a model is ideal. It will improve our understanding of the BLD phenomenon during cyclical movements, and also for improve our understanding of complex, unilateral and bilateral motor outputs. This will help to guide future research in the area, and increase the research base surrounding unilateral arm cycling, an under researched topic.

2.4 References

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Co-authorship Statement

My, Philip Edwards, contributions to this thesis are outlined below:

- Ms. Angie Antolinez (master's student) and I recruited all participants for this study and collected the data. I analyzed all of the data that was collected for this thesis.
- I prepared the manuscript and thesis with the help and guidance of my supervisor, Dr. Duane Button.
- Dr. Duane Button provided constructive feedback on the manuscript and thesis.

Chapter 3

Quantifying the Bilateral Deficit in Force During Maximal Arm Cycling Wingates.

Philip Edwards[1], Angie Antinolez[1], Duane C. Button[1,2*]

[1] School of Human Kinetics and Recreation and [2] Faculty of Medicine, Memorial University of Newfoundland, St. John's, NL, A1C 5S7

[*]Corresponding author:

Duane C. Button

School of Human Kinetics and Recreation

Memorial University of Newfoundland

230 Elizabeth Avenue

St. John's, Newfoundland, Canada, A1C 5S7

Phone: 709-864-4886

Fax: 709-864-3979

Email: dbutton@mun.ca

3.0 ABSTRACT

The bilateral deficit phenomenon (BLD) is a reduction in performance during a bilateral motor task when compared to the performance during the unilateral version of the same motor task. The objective of the current study was to determine if there was a BLD during maximal arm cycling Wingate tests. Thirteen healthy male participants performed three 30-second maximal arm cycling Wingate tests during three experimental sessions. Each session the participants completed Wingate tests with 1) both arms, 2) dominant arm, and 3) non-dominant arm at randomized intensities including 3% body weight (BW), 4% BW, or 5% BW. Instantaneous force data on the pedal axis was recorded and used to calculate the BLD. Data were analyzed using a three-way ANOVA with factors of intensity (3% BW, 4% BW, and 5% BW), time during the Wingate (1s – 10s, 11s – 20s, and 21s – 30 s), and position (1 o'clock position and 6 o'clock position). There was an overall BLD of -31.68 ± 21.20% ($p < .001$). The magnitude of the bilateral index (BI) value was significantly affected by the intensity of the Wingate ($p = .006$), and the time period of the Wingate ($p < .001$), but not the position. There were differences in the magnitude of the BLD across intensities and time periods. Overall, a BLD in force exists during maximal arm cycling Wingates and it is affected by fatigue and the movement velocity. Increases in movement velocity decrease the magnitude of the BLD and increased amounts of muscle fatigue increase the magnitude of the BLD.

KEYWORDS: Power, fatigue, upper body, velocity

3.1 INTRODUCTION

The BLD phenomenon is a physiological phenomenon that can be characterized by a reduction in performance during a bilateral motor task when compared to the unilateral performance during the same motor task. The BLD phenomenon is complex, highly variable, and subject to training adaptations, however, it has been shown to exist in many different motor outputs (Jakobi & Chilibeck, 2001; Janzen et al., 2006; Secher, 1975; Škarabot et al., 2016; Taniguchi, 1997, 1998). Numerous studies have explored the BLD phenomenon during isometric contractions (Behm et al., 2003; Buckthorpe et al., 2013; Cornwell et al., 2012; Herbert & Gandevia, 1996; Howard & Enoka, 1991; Kawakami et al., 1998; Koh et al., 1993; Oda & Moritani, 1995), and dynamic contractions (Cresswell & Ovendal, 2002; Dickin & Too, 2006; Janzen et al., 2006; Magnus & Farthing, 2008; Owings & Grabiner, 1998). The average magnitude of the BLD during dynamic and isometric contractions is approximately -11.7% and -8.6%, respectively (Škarabot et al., 2016), however, there are large variations in the magnitude across studies and different motor outputs.

There is only one study that has explored the BLD phenomenon during a cyclical movement (Dunstheimer et al., 2001). Dunstheimer et al. (2001) found a BLD in peak power and total mechanical work during leg cycling Wingates, but they did not measure the BLD in force. No studies have determined if there is a BLD in force during a cyclical movement, and no studies have assessed the BLD phenomenon using an upper body cyclical movement. It has been stated that the BLD phenomenon appears to be limited to twin-synchronous movements, but not simultaneous flexion and extension which can be seen during asynchronous cycling movements (Ohtsuki, 1983; Škarabot et al., 2016), however, there is little evidence to support this claim. The purposes of this study are to quantify the bilateral deficit in force during maximal arm cycling

Wingates and to determine if the magnitude is affected by the intensity, measured by the percentage of the participant's body weight (% BW), the time period of the Wingate (1s – 10s, 11s – 20s, 21s – 30s), or the position during arm cycling (1 o'clock position vs. 6 o'clock position). Currently, the effects of movement velocity and fatigue on the BLD are unclear. There are no established relationships between movement velocity and fatigue on the magnitude of the BLD. Incorporating Wingates with different intensities and measuring the BLD at three different time periods will help to determine the effects of movement velocity and fatigue on the BLD. Lastly, measuring at two different positions, 1 o'clock and 6 o'clock, where the triceps brachii and biceps brachii muscles are contributing the most to the movement (Chaytor et al., 2020), respectively, will help to determine if there are intermuscular differences in the magnitude of the BLD in force.

It is hypothesized that (1) there will be a significant bilateral deficit in force during arm cycling and (2) the magnitude of the bilateral deficit in force will be affected by the intensity (% BW), the time period of the Wingate (1s – 10s, 11s – 20s, 21s – 30s), and the position (1 o'clock vs. 6 o'clock). This study will contribute to our understanding of the BLD during cyclical movements, and it will increase our knowledge of intermuscular differences, and the effects of fatigue and movement velocity on the BLD.

3.2 METHODS

3.2.1 ETHICAL APPROVAL

Before data collection, all participants were informed of all potential risks and benefits of the study via verbal and written explanation and were given an opportunity to ask questions. All participants then gave written informed consent. This study was conducted in accordance with the Helsinki declaration and all protocols were approved by the Interdisciplinary Committee on

Ethics in Human Research at Memorial University of Newfoundland (ICEHR No. 20230904-HK).

3.2.2 PARTICIPANTS

Thirteen healthy male participants between the ages of 21 and 32 years old participated in the study (26.0 ± 3.3 years of age, 176.7 ± 4.0 cm, 81.2 ± 15.1 kg, one left hand dominant). Participants did not have prior experience with arm cycling Wingates. After providing informed consent, participants completed a Physical Activity Readiness Questionnaire (PAR-Q+) to ensure they could safely perform physical activity (Bredin et al., 2013). Hand dominance was then determined using the Edinburgh Handedness Inventory (Oldfield, 1971).

3.2.3 EXPERIMENTAL SETUP

3.2.3.1 ARM CYCLE ERGOMETER. All arm cycling trials were performed on a Velotron cycle ergometer (Dynafit Pro, RacerMate, Seattle, Wash., USA) modified for arm cycling (Figure 1). 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 that there was no reaching for the arm cranks at full-elbow extension. The ergometer height and chair distance were recorded for each participant and these values were used for all sessions. The hand cranks were locked 180° out-of-phase to perform asynchronous cycling. Participants were instructed to rest their inactive arm during unilateral Wingates on their lap to minimize any potential effects on the unilateral arm cycling movement.

3.2.4 FORCE DATA

Instantaneous force data on the pedal axis was recorded using Powerforce Smartfit sensors (Radlabor GmbH, Freiburg, Germany). All signals were sampled at a rate of 500 Hz and analog-digitally converted onto IMAGO® software (IMAGO Technologies GmbH, Freiburg, Germany) for data acquisition. The propulsion force or effective force which is tangential to the movement direction of the crank was recorded (Radlabor GmbH, Powerforce Smartfit User Manual).

3.2.5 WINGATE PERFORMANCE DATA

Wingate performance data was recorded using Velotron Wingate Software version 1.0 (RacerMate, Seattle, Wash., USA) at a sampling rate of 10 Hz. Five of the following variables were measured during each Wingate: (1) peak, mean, and minimum power (W), (2) peak and minimum RPM, (3) anaerobic capacity (mean power divided by body weight (W/kg)), (4) anaerobic power (peak power divided by body weight (W/kg)), and (5) fatigue index (peak power minus minimum power divided by test duration (W/s)) (Racermate, 2010, Velotron Wingate Software Users Guide, version 1.0).

3.2.6 EXPERIMENTAL PROTOCOL

3.2.6.1 FAMILIARIZATION SESSION. During the familiarization session, participants performed six 5-second arm cycling sprints at 3% BW, two sprints each with the dominant arm, the non-dominant arm, and both arms, in a randomized order. After completing the familiarization session, participants were given 48 hours of rest before their first experimental session.

3.2.6.2 EXPERIMENTAL SESSIONS. Subjects performed three 30-second maximal arm cycling Wingate tests during each of the three experimental sessions. One Wingate test was performed with both arms, the dominant arm, and the non-dominant arm in a random order. Twenty-minute rest intervals were provided between each Wingate test to minimize the effects of fatigue from the prior Wingate tests. The intensity of the Wingates was randomly determined before the session as either 3% BW, 4% BW, or 5% BW.

3.2.7 DATA ANALYSIS

All data analysis was performed offline using MATLAB software (MATLAB, Version R2022b, The Mathworks, Natick, MA, USA).

3.2.7.1 FORCE DATA. All force data were filtered using a 4th order lowpass Butterworth filter with a cut-off frequency of 50 Hz. Force data were resampled so that instantaneous force from each part of the cycle (0º to 360º or 12 o'clock position to 12 o'clock position) was recorded for each individual cycle during the Wingate (Figure 2). The digital trigger on the force sensor indicated when the right-hand crank was at the 6 o'clock position by displaying a "1" value. Every other position was indicated by a "0" value. Each cycle during the Wingate was quantified by finding a 1 value and then finding a subsequent 1 value. This constituted a full cycle. The instantaneous position of the crank was determined by calculating the total number of samples in the cycle and determining what percentage of the full cycle the crank was currently positioned.

The 1 o'clock (30º) and the 6 o'clock positions (180º) were used for data analysis because these two positions represented the two peaks of force production during the arm cycling Wingates. The mean propulsive force at the 1 o'clock and 6 o'clock positions were determined for all cycles, at all intensities from the 1s – 10s period, the 11s – 20s period, and the 21s – 30s period for every Wingate. The peak force at these positions for each cycle were then used to calculate the bilateral deficit.

The bilateral deficit was calculated as:

$$BI\ (\%) = (100 \times \frac{Sum\ of\ Bilateral\ force}{Sum\ of\ Unilateral\ force}) - 100$$

For example, to calculate the bilateral deficit in force at the 6 o'clock position, the sum of the mean bilateral forces at the 6 o'clock position for the dominant and non-dominant arms and the sum of the mean unilateral forces at the 6 o'clock position for the dominant and the non-dominant arms were determined, and the bilateral index value was calculated.

3.2.8 STATISTICAL ANALYSIS

3.2.8.1 ASSUMPTIONS. To determine if the data was normal, a Shapiro-Wilk test was performed. If the significance value was greater than .05, the data was considered to be normally distributed. Assumptions of sphericity were tested using the Mauchly test. If the significance value was greater than .05, the data did not violate the assumption of sphericity. If the significance value was less that .05, the epsilon value was used to determine what correction would be used. If the epsilon value was greater than 0.75, the Huynh-Feldt correction was used, however, if the epsilon value was less than 0.75, the Greenhouse-Geisser correction was used. All statistics will be performed using IBM's SPSS software (IBM SPSS, version 20.0; IBM Corp., Armonk, N.Y., USA).

3.2.8.2 DEPENDENT T-TEST. To determine if there was a significant bilateral deficit, a dependent (one-sample) t-test was used. If the bilateral index was significantly less than zero, this would indicate that there was a BLD. Conversely, if the BI was significantly greater than zero, this would indicate that there was a bilateral facilitation (BLF).

3.2.8.3 THREE-WAY REPEATED MEASURES ANOVA. Data were analyzed using a three-way repeated measures ANOVA design. The factors included intensity (3% BW, 4% BW, and 5% BW), time during the Wingate (1s – 10s, 11s – 20s, and 21s – 30 s), and position (1 o'clock position and 6 o'clock position). An alpha level of $p < 0.05$ was considered statistically significant. To determine if there were significant differences in the value of the BI across the intensities, time points, or positions, post-hoc pairwise comparisons using a Bonferroni correction were made. All data in tables and figures is reported as mean ± SD with a significance level of $p < .05$.

3.3 RESULTS

3.3.1 FORCE DATA

The mean force data from each factor for the bilateral and unilateral conditions are shown in Table 1. Data is reported as mean ± standard deviation.

3.3.2 BILATERAL DEFICIT IN FORCE

3.3.2.1 GRAND MEAN. There was a significant bilateral deficit in force during maximal arm cycling Wingates (-31.68 ± 21.20%, $p < .001$).

3.3.2.2 INTENSITY. There was a significant bilateral deficit in force at 3% BW (-37.5 ± 19.4%, $p < .001$), 4% BW (-36.2 ± 19.2%, $p < .001$), and 5% BW (-21.3 ± 21.1%, $p < .001$ (Figure 3 & Table 2). The magnitude of the BI value was significantly affected by the intensity of the Wingate, $F\ (1.134, 13.608) = 9.988$, $p = .006$. Pairwise comparisons revealed that there were significant differences in the magnitude of the BI value between 3% BW and 5% BW ($p = .035$), 4% BW and 5% BW ($p = .005$). There were not significant differences in the magnitude of the BI value between 3% BW and 4% BW.

3.3.2.3 TIME PERIOD DURING THE WINGATE. There was a significant bilateral deficit in force from 1s – 10s (-14.6 ± 14.5%, $p < .001$), 11s – 20s (-36.4 ± 16.4%, $p < .001$), and 21s – 30s (-44.0 ± 20.2%, $p < .001$) (Figure 4 & Table 2). The magnitude of the BI value was significantly affected by the time period of the Wingate, $F\ (2,24) = 88.857$, $p < .001$. Pairwise comparisons revealed that there were significant differences in the magnitude of the BI value between the 1s – 10 s period and the 11s – 20s period ($p < .001$) and the 1s – 10s period and the 21s – 30s period ($p < .001$). There were also significant differences in the magnitude of the BI value between the 11s – 20s period and the 21s – 30s period ($p = .013$).

3.3.2.4 POSITION. There was a significant bilateral deficit at the 1 o'clock position (-31.9 ± 22.2%, $p < .001$) and the 6 o'clock position (-31.4 ± 20.3%, $p < .001$) (Figure 5 & Table 2). The magnitude of the BI value was not affected by the position ($p = .889$). Pairwise comparisons revealed that there was not a significant difference in the magnitude of the BI value between the 1 o'clock position and the 6 o'clock position.

3.3.3 INTERACTIONS.

3.3.3.1 INTENSITY AND TIME. There was a significant interaction between the intensity of the Wingate (% BW) and the time period of the Wingate, F (4, 48) = 5.156, $p = .002$ (Figure 6 & Table 3). Post-hoc pairwise comparisons showed that there was a significant difference in the magnitude of the BI value during the 11s – 20s period of the Wingate between 4% BW and 5% BW (-14.97%, $p = .018$), and a non-significant difference between 3% BW and 5% BW (-14.56%, $p = .129$). There were also significant differences in the magnitude of the BI values during the 21s – 30s period of the Wingate between 3% BW and 5% BW (-27.13%, $p = .013$), and 4% BW and 5% BW (-23.05, $p = .003$).

3.3.3.2 INTENSITY AND POSITION. There was not a significant interaction between intensity and position (Figure 7 & Table 4). This tells us that the magnitude of the BI values did not differ between intensities at the 1 o'clock and 6 o'clock positions.

3.3.3.3 TIME AND POSITION. There was not a significant interaction between time and position (Figure 8 & Table 5). This tells us that the magnitude of the BI values did not differ between time periods at the 1 o'clock and 6 o'clock positions.

3.3.4 WINGATE PERFORMANCE DATA

The mean and minimum power and RPM, anerobic capacity, anerobic power, fatigue index, and total work are reported in Table 6.

3.4 DISCUSSION

The most important findings of the present study were that (1) a bilateral deficit exists during arm cycling, (2) the magnitude of the BLD was affected by the intensity and time period, but not the position, and (3) there was a significant interaction between the intensity of the Wingate and the time period of the Wingate. These findings show that a BLD in force can exist during cyclical movement and that the magnitude of the BLD is affected by movement velocity, fatigue, and other measures of Wingate performance. No studies had previously demonstrated the presence of a BLD in force during a cyclical movement. This study was able to quantify the BLD in force and enables future exploration of the BLD phenomenon during cyclical movements. This will help to determine the mechanisms underlying the BLD during cyclical movement.

3.4.1 A BILATERAL DEFICIT IN FORCE EXISTS DURING ARM CYCLING.

Numerous other studies have found a bilateral deficit in force during dynamic (Cresswell & Ovendal, 2002; Dickin & Too, 2006; Kuruganti & Seaman, 2006; Magnus & Farthing, 2008; Owings & Grabiner, 1998), and isometric contractions (Behm et al., 2003; Botton et al., 2013; Buckthorpe et al., 2013; Koh et al., 1993; Ohtsuki, 1983), however, no study had determined the presence of a BLD in force during a cyclical movement. It had been stated previously that the

BLD phenomenon is limited to twin-synchronous movements, but not simultaneous flexion and extension (Ohtsuki, 1983; Škarabot et al., 2016). Archontides and Fazey (1993) speculated that this was because the area controlling the flexors on one side of the body is not interconnected with the area that controls the extensors on the contralateral side of the body. This study provides evidence to the contrary and demonstrates that the BLD phenomenon can exist during asynchronous movements involving simultaneous flexion and extension. Future studies should assess the presence of a BLD during other asynchronous movements. This will help to determine if the results from this study are replicable, and it may expose new potential mechanisms for the BLD phenomenon.

The magnitude of the BLD in force during maximal arm cycling Wingates (-31.68%) was quite large compared to the average magnitude during dynamic (-11.7%) and isometric contractions (-8.6%) (Škarabot et al., 2016). The magnitude of the BLD in force was closer to those observed during ballistic or explosive contractions which have been shown to surpass a 30% BLD (Pain, 2014; Rejc et al., 2010; Samozino et al., 2014). This makes sense as maximal arm cycling Wingates are a highly explosive movement, with high movement velocities. It has been stated that the mechanisms that underlie the BLD phenomenon during ballistic or explosive movements likely differ from other contraction types (Škarabot et al., 2016) since they can at least be partially explained by changes in the force-velocity relationship (Bobbert et al., 2006; Samozino et al., 2014) or by differences in muscle coordination (Rejc et al., 2010). It is likely that the BLD in force during maximal arm cycling Wingates is due to a combination of changes in both the force-velocity relationship and muscle coordination. Figure 9 and Table 6 clearly show that there are differences in the movement velocity, as measured by RPM, between the unilateral Wingates and the bilateral Wingates. Bilateral Wingates at all intensities had a higher movement velocity than the unilateral Wingates. This may have led to a deficit in bilateral force since movements at higher velocities are generally less forceful due to the inverse relationship between force and velocity (Jaric, 2015).

The BLD in force could have also been due, at least partially, to changes in muscle coordination during the unilateral and bilateral Wingates. Changes in muscle activation patterns and kinematics have been observed during fatiguing cycling protocols (Dingwell et al., 2008; Quittmann et al., 2022), thus, it is possible that kinematic changes throughout the Wingates could be partially responsible for the BLD in force that was observed in this study. Although there are no studies that have compared the kinematics of maximal unilateral arm cycling Wingates to maximal bilateral arm cycling Wingates, solely based on observation during the data collection process, there were clear differences between the two movements. Participants tended to have a greater amount of trunk torsion during unilateral Wingates, which likely contributed to the BLD in force. A study comparing the kinematics and EMG responses of unilateral arm cycling Wingates to bilateral arm cycling Wingates would provide useful insight into the biomechanical mechanisms that may be responsible for the BLD in force during arm cycling.

3.4.2 THE MAGNITUDE OF THE BLD IS AFFECTED BY FATIGUE.

The magnitude of the BLD increased throughout the Wingates as shown in Figures 4 & 6. This finding demonstrates that the accumulation of muscle fatigue during maximal arm cycling Wingates can affect the magnitude of the BLD in force. Few studies assessing the BLD phenomenon have assessed the effects of fatigue on the magnitude of the BLD. Studies from Owing and Grabiner (1998), and Vandervoort et al. (1984, 1987) failed to demonstrate a clear relationship between fatigue and the magnitude of the BLD. Vandervoort et al. (1984) showed that during combined hip and knee extension, bilateral force tended to decrease less than unilateral force. However, a subsequent study from their lab using the bench press movement showed that fatigue accumulated quicker in the bilateral bench press (Vandervoort et al., 1987). Owings and Grabiner (1998) found that fatigue increased the magnitude of the BLD during leg extension, but only at 30º/s, not 150º/s. The effects of fatigue on the BLD seem to be affected by the motor output, and also the movement velocity.

During arm cycling Wingates, regardless of the intensity that was used, the magnitude of the BLD increased over time. As shown by Figures 10-15, the bilateral force tended to decrease over time, with the exception of 5% BW, and the unilateral force tended to increase over time. Since the bilateral and unilateral forces tended to move in different directions over time, the increase in the magnitude of the BLD in force makes sense. During the unilateral Wingates the participants were less able to maintain the power output and the required force to complete each cycle was greater than during bilateral Wingates. This is because during unilateral Wingates, there is only one limb contributing to the cycling movement. This explains why the BLD in force increased with time. It seems that power output and force may be negatively correlated at certain points during arm cycling Wingates. This is likely why as the power outputs decreased throughout the Wingate, the BLD in force increased.

Although 3% BW and 4% BW followed a similar, linear increase in the magnitude of the BLD in force over time, 5% BW displayed a different pattern. There was a minimal difference in the magnitude of the BLD between 11-20s and 21-30s at 5% BW (Figure 6). This is likely because the power output decreased earlier during 5% BW Wingates than at 3% BW and 4% BW (Figure 9). There was a much sharper decline in RPM during 5% BW arm cycling Wingates, however, the RPM remained consistent at a low level from approximately the 10s point and onwards. This likely explains why there was a minimal difference in the magnitude between 11-

20s and 21-30s. There was very little change in RPM, thus, there was a smaller change in the magnitude of the BLD.

3.4.3 THE MAGNITUDE OF THE BLD IS AFFECTED BY MOVEMENT VELOCITY.

During maximal arm cycling Wingates as the movement velocity increases, so too does the magnitude of the BLD. The largest BLD was observed at 3% BW (-37.5%) and the smallest BLD was at 5% BW (-21.3%). As Figure 3 shows, with increases in intensity, the magnitude of the BLD became smaller, likely due to changes in the force-velocity relationship.

The relationship between movement velocity and the magnitude of the BLD is ambiguous. Some studies have shown that an increase in movement velocity tends to increase the magnitude of the BLD (Dickin & Too, 2006; Koh et al., 1993; Vandervoort et al., 1984), however, other studies have shown conflicting results (Brown et al., 1994; Kuruganti & Seaman, 2006). In this study, as the intensity decreased, the BLD in force increased. This increase in intensity seemed to be associated with an increase in movement velocity (Figure 3). The larger BLD in force at greater velocities is likely due to the greater differences in the movement velocity between bilateral and unilateral Wingates. At 3% BW there was the greatest difference between unilateral and bilateral Wingates in terms of RPM, and at 5% BW there was the least difference. At different intensities, the time course of fatigue is different for bilateral and unilateral Wingates. This may be due to different rates of accumulation of lactic acid and metabolites, or changes in peripheral and central fatigue. It may also be due to different levels of efficiency in the unilateral and bilateral arm cycling movement. A study comparing the metabolic and neural changes in response to unilateral and bilateral arm cycling Wingates at different intensities would be valuable to determine the potential neural and physiological mechanisms of the BLD during arm cycling. As stated before, another study comparing the kinematics and EMG responses of unilateral arm cycling Wingates to bilateral arm cycling Wingates would provide useful insight into the efficiency of each respective movement, and it may help to explain the BLD in force.

3.4.4 THE MAGNITUDE OF THE BLD IS DOES NOT DIFFER BETWEEN POSITIONS

The magnitude of the BLD did not differ between the 1 o'clock and 6 o'clock positions (Figure 4). This finding shows that there are no significant differences in the magnitude of the BLD between the biceps brachii and triceps brachii muscles during arm cycling. Studies from Aune et al. (2013) and Kawakami et al. (1998) have shown that there are significant differences in the magnitude of the BLD across muscles. Kawakami et al. (1998) measured the BLD in force during plantar flexion in the gastrocnemius, a muscle with more type II muscle fibres, and the soleus muscle. They found that the BLD was greater in the gastrocnemius muscle and suggested that this was due to greater inhibition of type II muscle fibers. Aune et al. (2013) measured the BLD in shoulder flexion and index finger flexion to determine if the amount of transcallosal and corticospinal projections between muscles affects the magnitude of the BLD. A greater BLD was found in shoulder flexion which the authors suggested was due to greater amounts of higher order neural inhibition in the deltoid muscle (Aune et al., 2013). In our study, there were no significant differences in the magnitude of the BLD between the triceps brachii and biceps brachii muscles. There are differences in muscle fibre composition and the amount of type II muscle fibres between the triceps brachii and biceps brachii muscles (Elder et al., 1982), however, this did not significantly affect the magnitude of the BLD in force. Inhibition of type II muscle fibres likely did not affect the magnitude of the BLD during arm cycling. Arm cycling studies have shown that there is inhibition to both the triceps brachii and biceps brachii muscles during arm cycling (Benson et al., 2021; Herat, 2022), however, it does not seem that this inhibition differently affects the magnitude of the BLD. Future work should further examine the inhibitory processes that occur during arm cycling and provide an in-depth description of the differences in inhibition between the triceps and biceps brachii muscles. This will help to determine why the magnitude of the BLD does not differ between the triceps brachii and biceps brachii muscles.

3.4.5 METHODOLOGICAL CONSIDERATIONS.

There were several important methodological considerations that required attention before conducting the study. Firstly, and most importantly, was the determination of the %BW that would be used during the bilateral and unilateral Wingates. In previous work from our lab, 5% BW was the standard intensity used for bilateral arm cycling Wingates (Pearcey et al., 2016). However, our lab had never performed unilateral arm cycling Wingates. It was unclear if the participant should have cycled against the same resistance level as the bilateral Wingates or if the resistance should be half of what was used during the bilateral Wingates. Dunstheimer et al. (2001) utilized 49% of the bilateral load during unilateral leg cycling Wingates in their investigation of the BLD phenomenon. However, it is unclear if this is the optimal strategy for setting resistance levels. One cannot assume that unilateral power outputs are exactly half of bilateral power outputs. Bilateral asymmetries exist during cycling movements and people do not always produce equal amounts of force with each limb during cycling (Carpes et al., 2010), thus, taking the bilateral load and halving the resistance level is not an exact solution to providing an equal relative load. There were many ways to potentially determine the resistance level during unilateral arm cycling Wingates such as grip strength ratios or peak power output ratios between limbs, however, no one has validated the accuracy of these methods. As an additional sub purpose of this study, we hoped to determine the optimal intensities to utilize during unilateral and bilateral arm cycling Wingates. Thus, it was decided to perform the bilateral and unilateral arm cycling Wingates at 3% BW, 4% BW, and 5% BW. After data collection and analysis, it appears that 3% BW unilaterally and 5% BW bilaterally closely match each other in terms of movement velocity (Figure 9). It is unclear what % BW is optimal to match 4% BW and 3% BW bilateral Wingates as we did not utilize intensities below 3% BW for unilateral Wingates. It is also unclear if matching movement velocity is the optimal way to equate relative intensities. Overall, there were many potential ways to determine the intensity for the unilateral and bilateral Wingates. It is unclear if the methodology that we used was optimal, however, we were able to generate useful reference data that will help when performing future studies on the topic.

Another important methodological consideration for this study was determining what positions and time periods we would use in our statistical analysis. As mentioned in the methods section, the 1 o'clock position and the 6 o'clock position were selected for data analysis because these two positions closely represented the two peaks of force production during the arm cycling Wingates. One could analyze the data at different positions and potentially find different results, however, it was reasonable to evaluate the data at the highest point of force production during the flexion and the extension phases of arm cycling. With regards to the time periods that were used in the data analysis, one could have binned the data in numerous different ways. Using 10s bins created a beginning, middle, and end period of the Wingate and enabled us to evaluate the time course of fatigue and its effects on the magnitude of the BLD. Bins of different lengths could have been used and again, different results could be found, however, 10s bins were rational.

3.5 CONCLUSION

This study was the first to quantify the BLD in force and to examine the effects of different intensities, time periods, and positions on the magnitude of the BLD during maximal arm cycling Wingates. This study showed that there was a significant BLD in force during arm cycling and that it was affected by the intensity and time period, but not the position. Based on these results, it is evident that fatigue and movement velocity affect the magnitude of the BLD in force during maximal arm cycling Wingates. Future studies should measure the kinematic, physiological, and electromyographic responses during maximal arm cycling Wingates to help determine the neuromechanical and physiological mechanisms underlying the BLD in force. This will contribute to an improved understanding of the BLD phenomenon and complex cyclical movements like arm cycling.

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Table 1. Mean sum of bilateral and unilateral force data for each factor (n = 13).

Intensity	Time	Condition	Position	Force (N) (MEAN ± SD)
3% BW	1-10s	Bilateral	1 O'CLOCK	191.39 ± 36.01

			6 O'CLOCK	256.96 ± 36.55
		Unilateral	1 O'CLOCK	263.25 ± 43.25
			6 O'CLOCK	299.84 ± 42.42
	11-20s	Bilateral	1 O'CLOCK	173.74 ± 32.84
			6 O'CLOCK	183.28 ± 23.78
		Unilateral	1 O'CLOCK	298.55 ± 52.75
			6 O'CLOCK	322.36 ± 48.66
	21-30s	Bilateral	1 O'CLOCK	140.81 ± 28.86
			6 O'CLOCK	158.16 ± 21.63
		Unilateral	1 O'CLOCK	328.24 ± 61.92
			6 O'CLOCK	350.72 ± 59.73
4% BW	1-10s	Bilateral	1 O'CLOCK	233.91 ± 34.26
			6 O'CLOCK	277.10 ± 43.24
		Unilateral	1 O'CLOCK	283.20 ± 39.15
			6 O'CLOCK	333.68 ± 45.20
	11-20s	Bilateral	1 O'CLOCK	212.76 ± 31.36
			6 O'CLOCK	229.39 ± 31.49
		Unilateral	1 O'CLOCK	380.35 ± 67.61
			6 O'CLOCK	395.96 ± 64.66
	21-30s	Bilateral	1 O'CLOCK	199.56 ± 36.29
			6 O'CLOCK	215.24 ± 34.38
		Unilateral	1 O'CLOCK	423.97 ± 71.46
			6 O'CLOCK	422.62 ± 57.48

5% BW	1-10s	Bilateral	1 O'CLOCK	257.25 ± 40.51
			6 O'CLOCK	310.69 ± 48.26
		Unilateral	1 O'CLOCK	291.56 ± 48.35
			6 O'CLOCK	350.43 ± 52.28
	11-20s	Bilateral	1 O'CLOCK	302.31 ± 53.52
			6 O'CLOCK	315.77 ± 53.68
		Unilateral	1 O'CLOCK	400.75 ± 64.47
			6 O'CLOCK	455.95 ± 60.88
	21-30s	Bilateral	1 O'CLOCK	316.66 ± 55.66
			6 O'CLOCK	325.08 ± 63.99
		Unilateral	1 O'CLOCK	441.21 ± 66.89
			6 O'CLOCK	459.39 ± 59.88

Table 2. Mean bilateral index values for each factor and condition (n = 13).

Factors	Conditions	Bilateral Index (%) (MEAN ± SD)	Significance	95% Confidence Interval
Intensity	3% BW	-37.5 ± 19.4%	$p < .001$	(-41.9%, -33.1%)

	4% BW	-36.2 ± 19.2%	p < .001	(-40.6%, -31.9%)
	5% BW	-21.3 ± 21.1%	p < .001	(-26.1%, -16.5%)
Time	1s – 10s	-14.6 ± 14.5%	p < .001	(-17.8%, -11.3%)
	11s – 20s	-36.4 ± 16.4%	p < .001	(-40.1%, -32.8%)
	21s – 30s	-44.0 ± 20.2%	p < .001	(-48.6%, -39.5%)
Position	1 o'clock	-31.9 ± 22.2%	p < .001	(-36.0%, -27.9%)
	6 o'clock	-31.4 ± 20.3%	p < .001	(-35.2%, -27.7%)

Table 3. Mean bilateral index values for each intensity at each time period (n = 13).

Intensity	Time	Bilateral Index (%) (MEAN ± SD)	Significance	95% Confidence Interval
3% BW	1-10s	-16.90 ± 11.29%	p < .001	(-21.46%, -12.34%)

	11-20s	-41.16 ± 12.46%	$p < .001$	(-46.20%, -36.13%)
	21-30s	-54.45 ± 11.32%	$p < .001$	(-59.02%, -49.88%)
4% BW	1-10s	-16.80 ± 13.95%	$p < .001$	(-22.43%, -11.16%)
	11-20s	-41.57 ± 11.76%	$p < .001$	(-46.32%, -36.82%)
	21-30s	-50.37 ± 13.22%	$p < .001$	(-55.71%, -45.03%)
5% BW	1-10s	-10.00 ± 17.07%	$p = .006$	(-16.90%, -3.11%)
	11-20s	-26.60 ± 19.48%	$p < .001$	(-34.47%, -18.73%)
	21-30s	-27.32 ± 22.52%	$p < .001$	(-36.42%, -18.23%)

Table 4. Mean bilateral index values for each intensity at each position (n = 13).

Intensity	Position	Bilateral Index (%) (MEAN ± SD)	Significance	95% Confidence Interval
3% BW	1 O'CLOCK	-39.16 ± 18.50%	$p < .001$	(-45.16%, -33.16%)

	6 O'CLOCK	-35.85 ± 20.46%	p < .001	(-42.48%, -29.21%)
4% BW	1 O'CLOCK	-36.90 ± 19.77%	p < .001	(-43.31%, -30.49%)
	6 O'CLOCK	-35.59% ± 18.89%	p < .001	(-41.71%, -29.47%)
5% BW	1 O'CLOCK	-19.71% ± 23.10%	p < .001	(-27.20%, -12.23%)
	6 O'CLOCK	-22.90 ± 19.17%	p < .001	(-29.12%, -16.69%)

Table 5. Mean bilateral index values for each time period at each position (n = 13).

Time	Position	Bilateral Index (%) (MEAN ± SD)	Significance	95% Confidence Interval
1-10s	1 O'CLOCK	-15.39 ± 15.90%	p < .001	(-20.55%, -10.24%)
	6 O'CLOCK	-13.74% ± 13.07%	p < .001	(-17.97%, -9.50%)
11-20s	1 O'CLOCK	-35.71 ± 17.48%	p < .001	(-41.38%, -30.04%)
	6 O'CLOCK	-37.17 ± 15.36%	p < .001	(-42.15%, -32.19%)
21-30s	1 O'CLOCK	-44.67 ± 21.88%	p < .001	(-51.76%, -37.58%)
	6 O'CLOCK	-43.42 ± 18.60%	p < .001	(-49.45%, -37.39%)

Table 6. Wingate performance data at 3 % BW ,4 % BW, & 5% BW with both arms, the dominant arm, and the non-dominant arm. Values are presented as the mean (SD) (n = 13).

Intensity	Condition	Mean Power (W)	Min Power (W)	Mean RPM	Min RPM	Anerobic Capacity (mean W/kg)	Anerobic Power (peak W/kg)	Fatigue Index (W/s)	Total Work (J)

3%	B	316.85 (71.35)	256.77 (70.08)	131.08 (34.58)	101.85 (18.00)	3.84 (1.05)	4.28 (0.88)	5.38 (3.59)	9506.36 (2853.98)
	D	189.85 (34.38)	101.85 (46.30)	79.77 (30.44)	40.38 (17.90)	2.34 (0.98)	3.44 (0.91)	6.45 (3.52)	5695.21 (2615.36)
	N	180.08 (33.97)	89.54 (40.97)	75.69 (30.29)	38.08 (19.43)	2.22 (0.97)	3.36 (0.92)	6.48 (3.52)	5404.22 (2612.30)
4%	B	331.77 (89.80)	210.69 (83.37)	103.31 (32.00)	66.46 (24.69)	4.05 (1.08)	4.86 (0.89)	8.17 (3.54)	9955.10 (2922.30)
	D	158.69 (34.71)	50.46 (28.66)	51.00 (30.17)	15.69 (9.62)	1.98 (0.98)	4.43 (0.87)	10.64 (3.47)	4759.82 (2613.06)
	N	153.92 (32.74)	49.69 (32.28)	49.23 (30.16)	15.54 (11.33)	1.93 (0.98)	4.44 (0.87)	10.71 (3.48)	4617.72 (2613.21)
5%	B	300.62 (71.48)	150.69 (65.44)	76.23 (30.46)	38.38 (18.63)	3.73 (1.06)	5.63 (0.92)	11.02 (3.51)	9019.62 (2812.85)
	D	148.54 (29.64)	51.00 (23.33)	37.85 (30.42)	12.31 (3.59)	1.85 (0.98)	5.61 (0.91)	13.87 (3.64)	4453.21 (2613.19)
	N	142.77 (29.85)	52.31 (23.94)	36.31 (30.48)	12.54 (3.93)	1.76 (0.98)	5.55 (0.91)	13.61 (3.62)	4285.98 (2616.07)

Figure Legend

Figure 1. Experimental set-up for arm cycling Wingates.

Figure 2. Example of how the force was resampled from 0º to 360º for each cycle for one participant during a Wingate. Notice how each individual cycle is represented in the graph. Forces were sampled at the 1 o'clock and 6 o'clock positions.

Figure 3. Bilateral index values at 3% BW, 4% BW, and 5% BW during maximal arm cycling Wingates.

Figure 4. Bilateral index values at 1s – 10s, 11s – 20s, and 21s – 30s during maximal arm cycling Wingates.

Figure 5. Bilateral index values at the 1 o'clock and 6 o'clock position during maximal arm cycling Wingates.

Figure 6. Bilateral index values at each time period at all intensities.

Figure 7. Bilateral index values at 3% BW, 4% BW, and 5% BW at the 1 o'clock position and the 6 o'clock position.

Figure 8. Bilateral index values at all three time periods at the 1 o'clock and 6 o'clock positions.

Figure 9. RPM during maximal arm cycling Wingates at 3% BW, 4% BW, and 5% BW with both arms, the non-dominant arm, and the dominant arm.

Figure 10. Total bilateral force and RPM at 3% BW. Force data is smoothed.

Figure 11. Total unilateral force and RPM at 3% BW. Force data is smoothed.

Figure 12. Total bilateral force and RPM at 4% BW. Force data is smoothed.

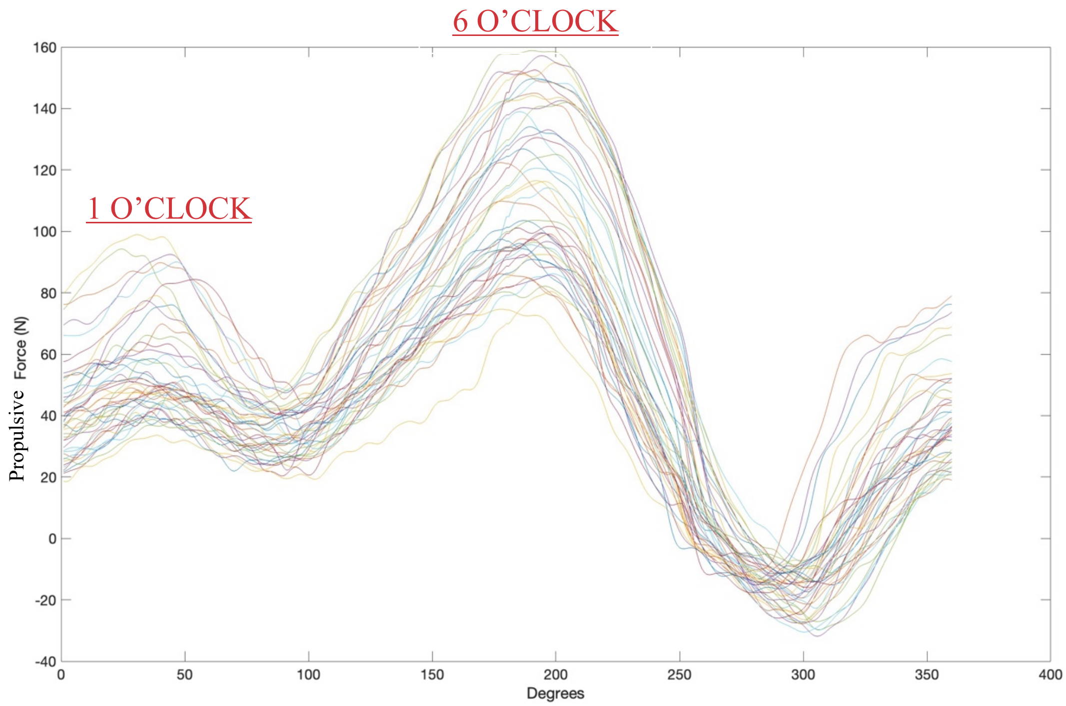
Figure 13. Total unilateral force and RPM at 4% BW. Force data is smoothed.

Figure 14. Total bilateral force and RPM at 5% BW. Force data is smoothed.

Figure 15. Total unilateral force and RPM at 5% BW. Force data is smoothed.

Figure 1.

Figure 2.



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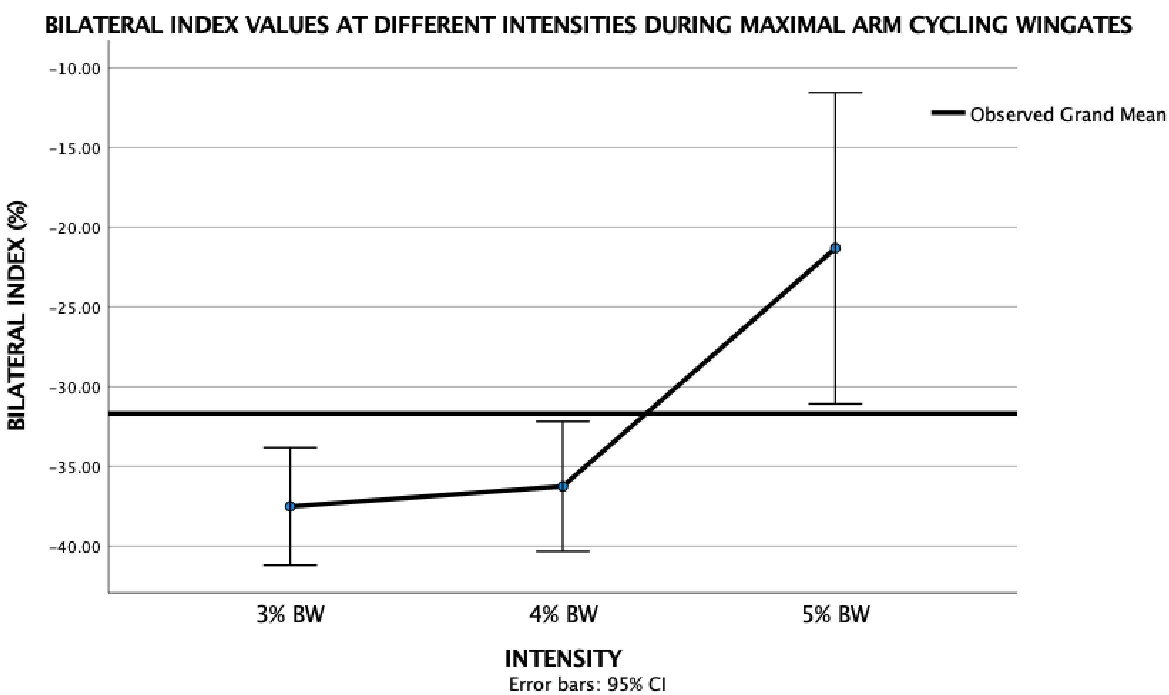

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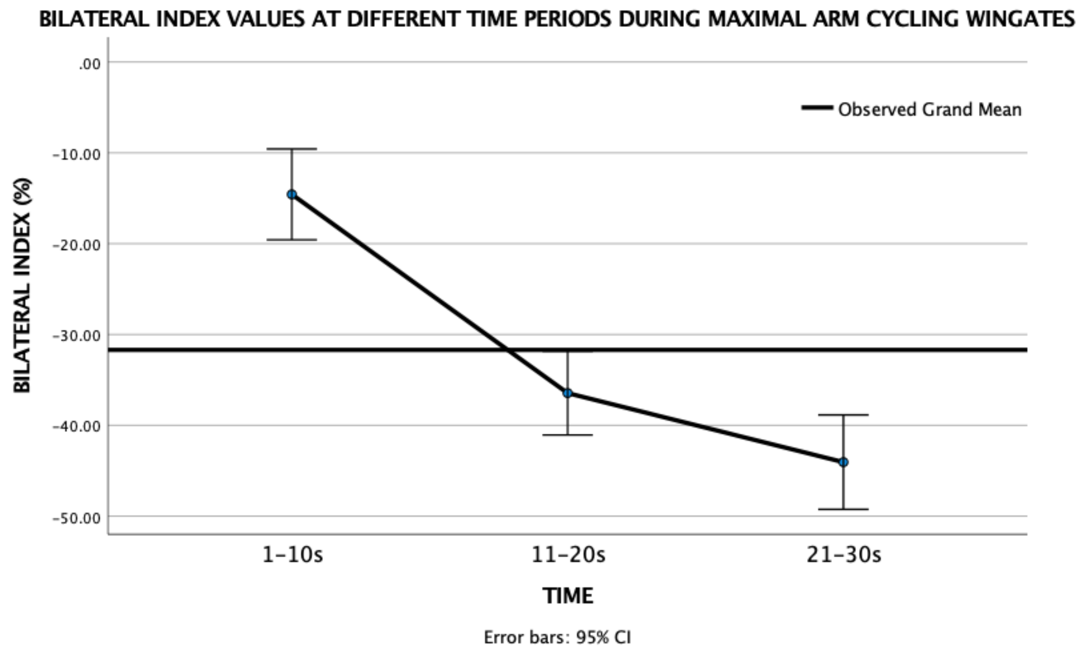

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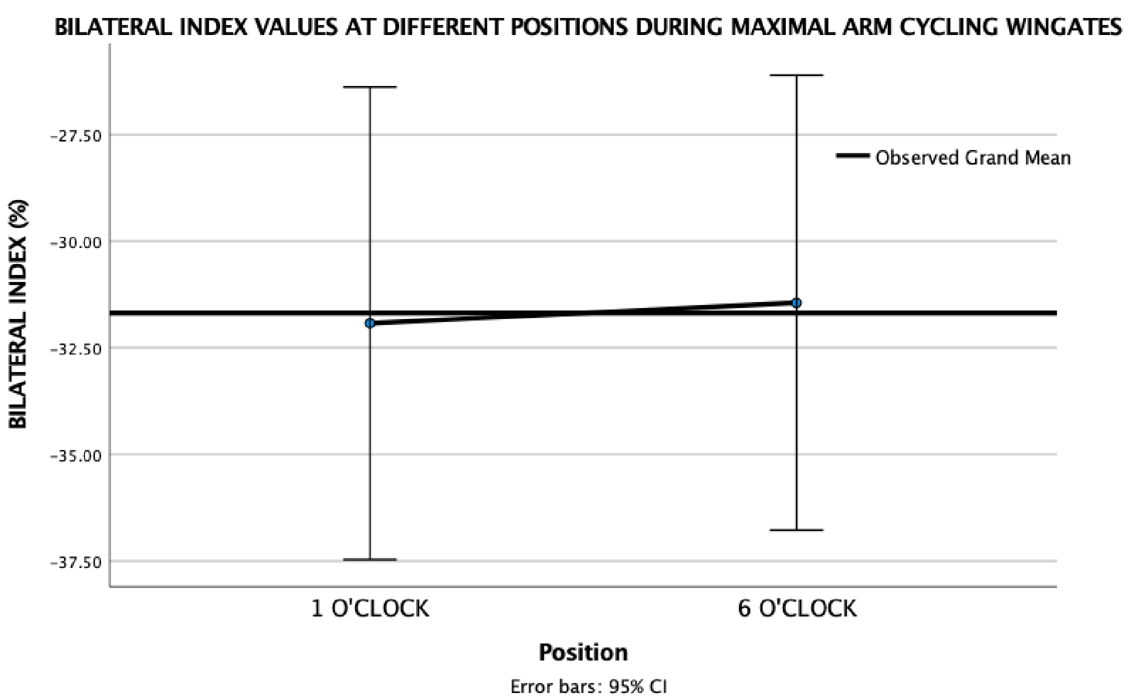

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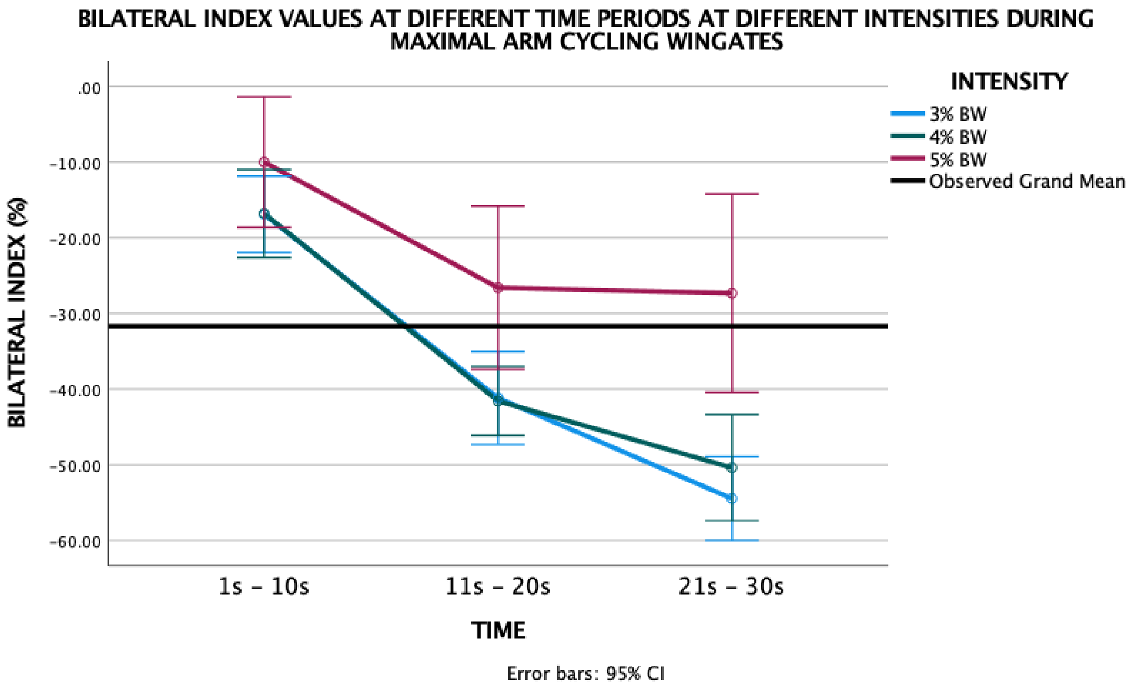

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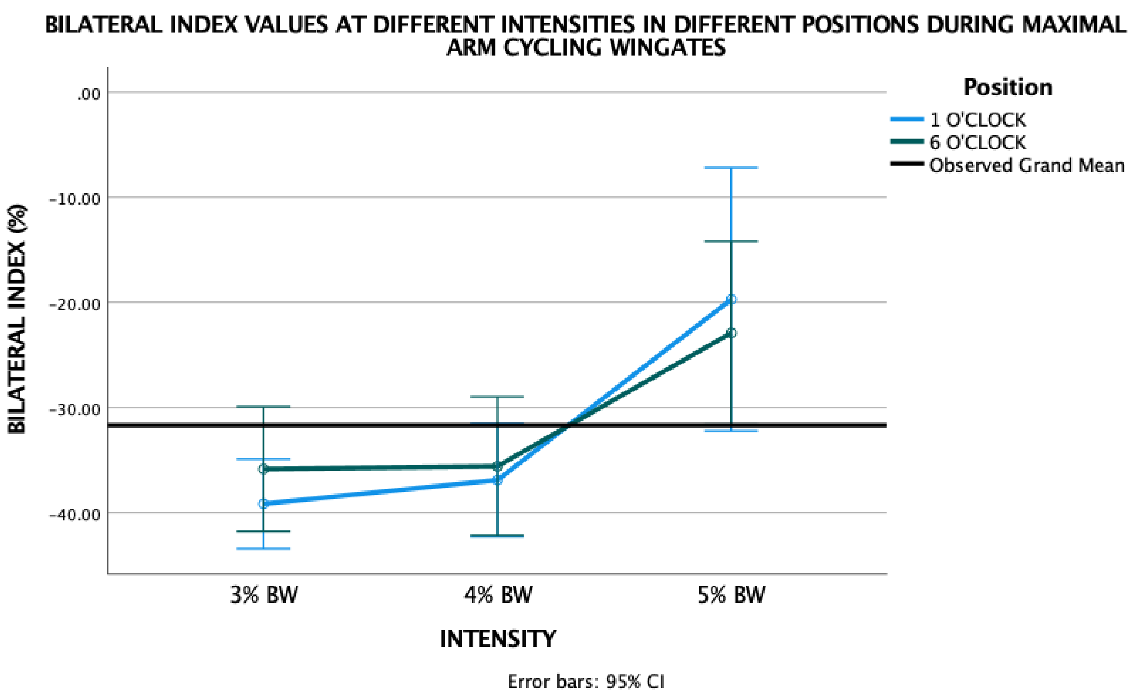

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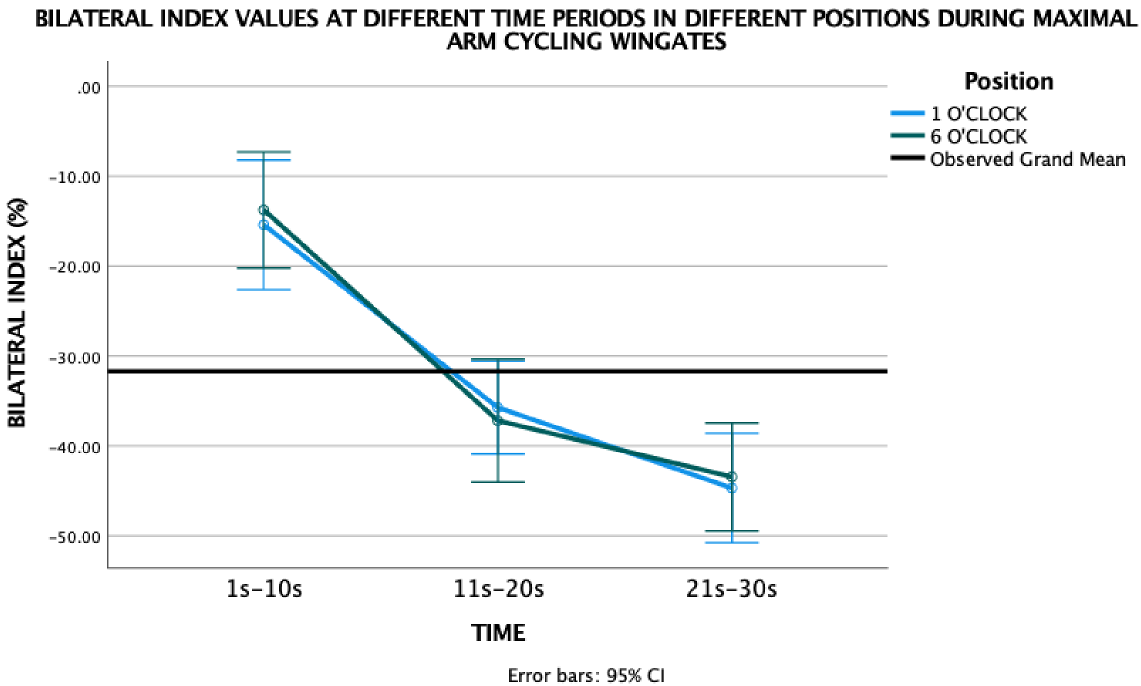

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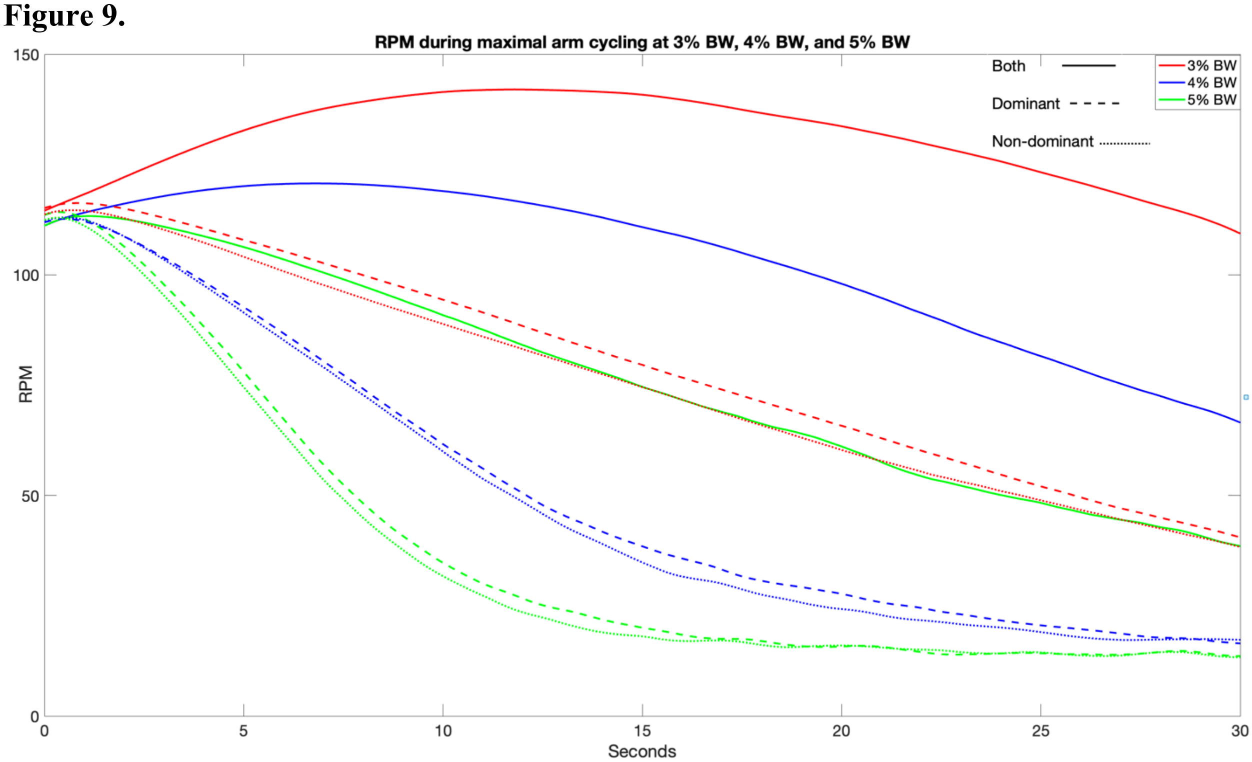

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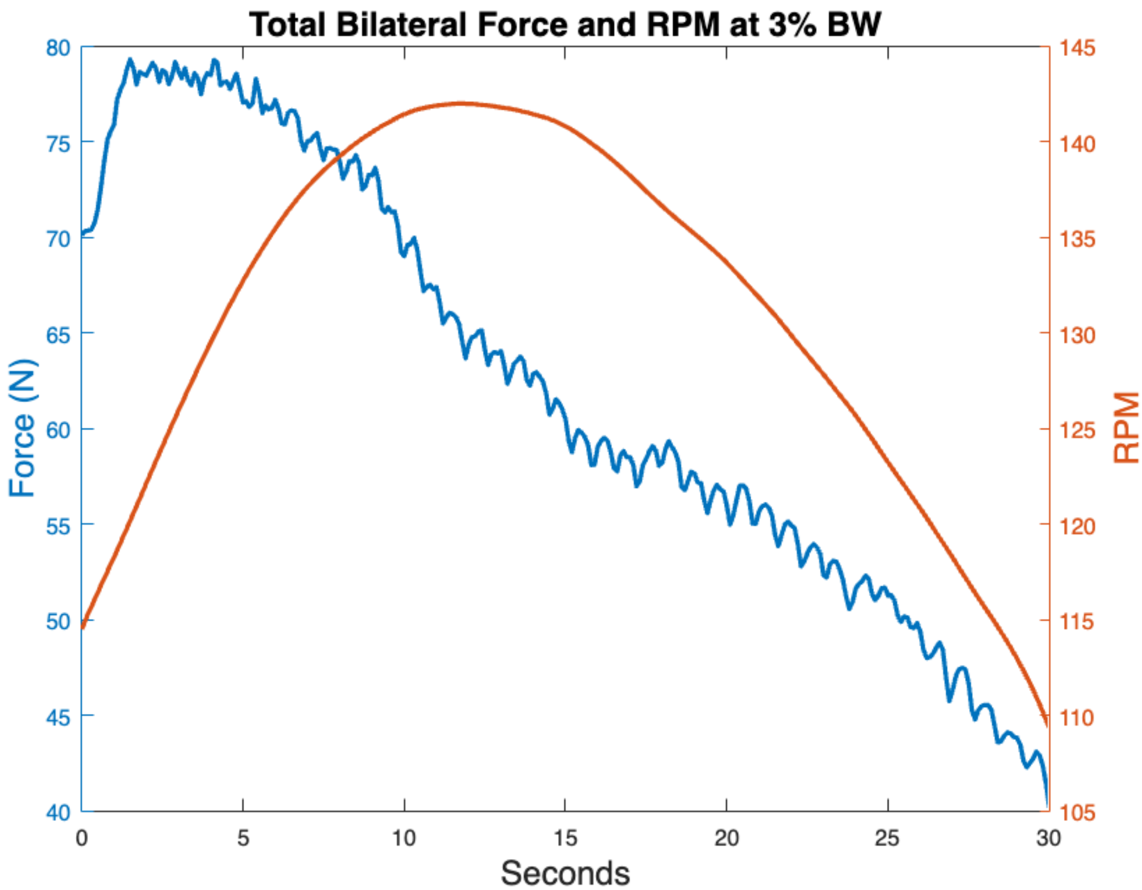
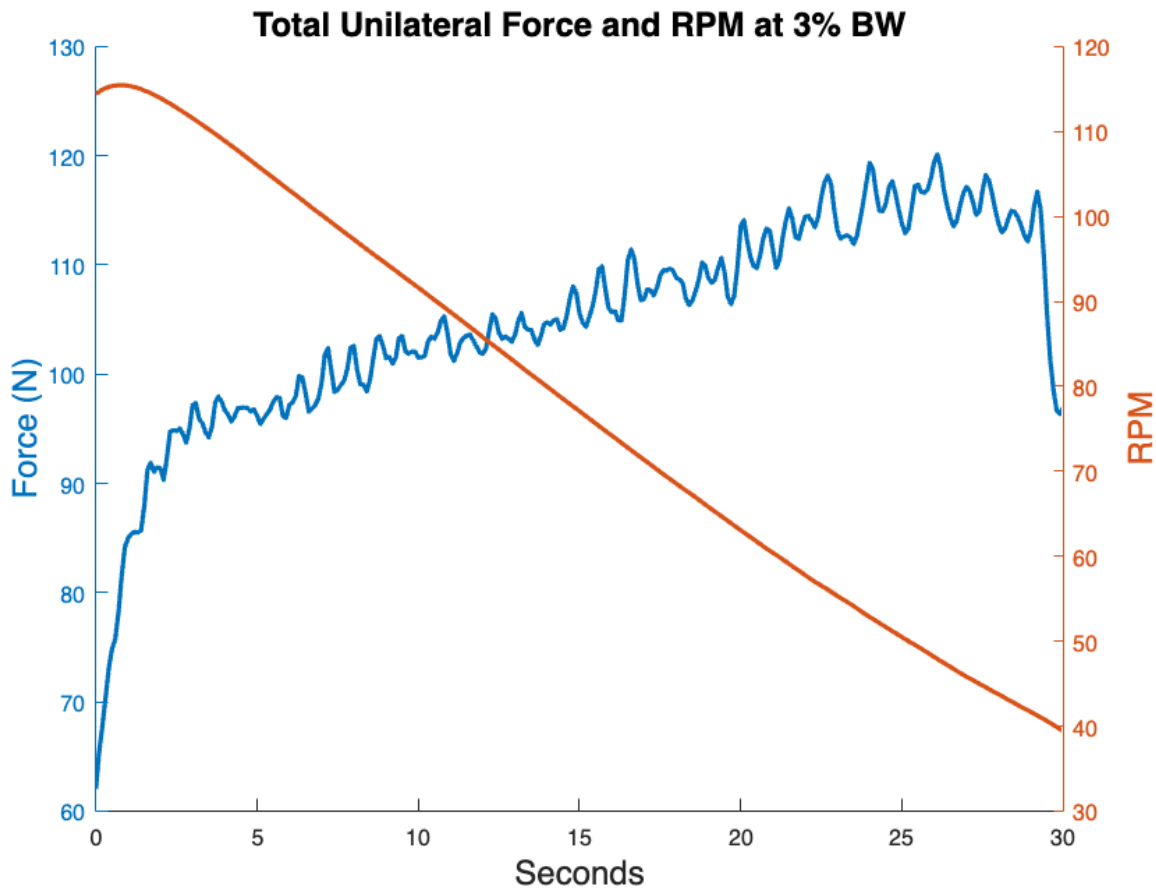


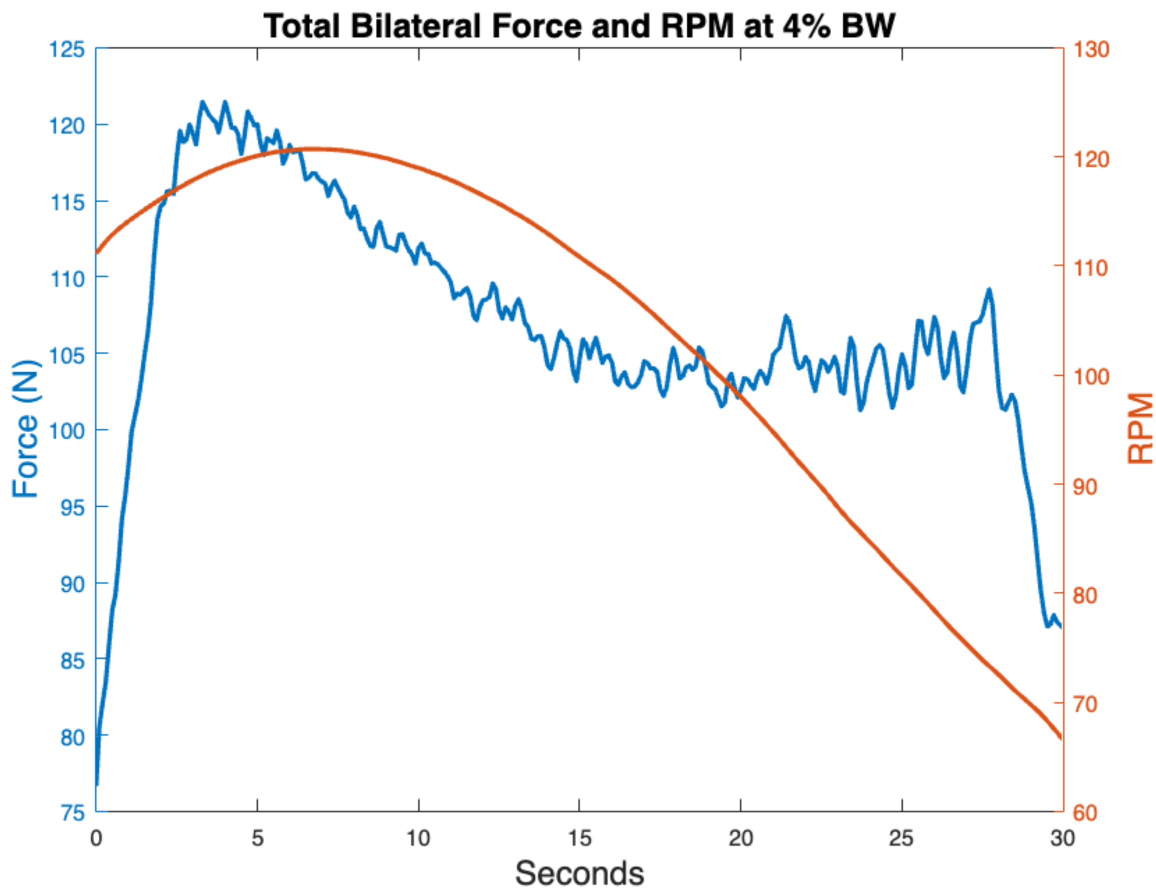
Total Bilateral Force and RPM at 3% BW
Force (N)
RPM
Seconds
80
75
70
65
60
55
50
45
40
145
140
135
130
125
120
115
110
105
0
5
10
15
20
25
30

Figure 11.



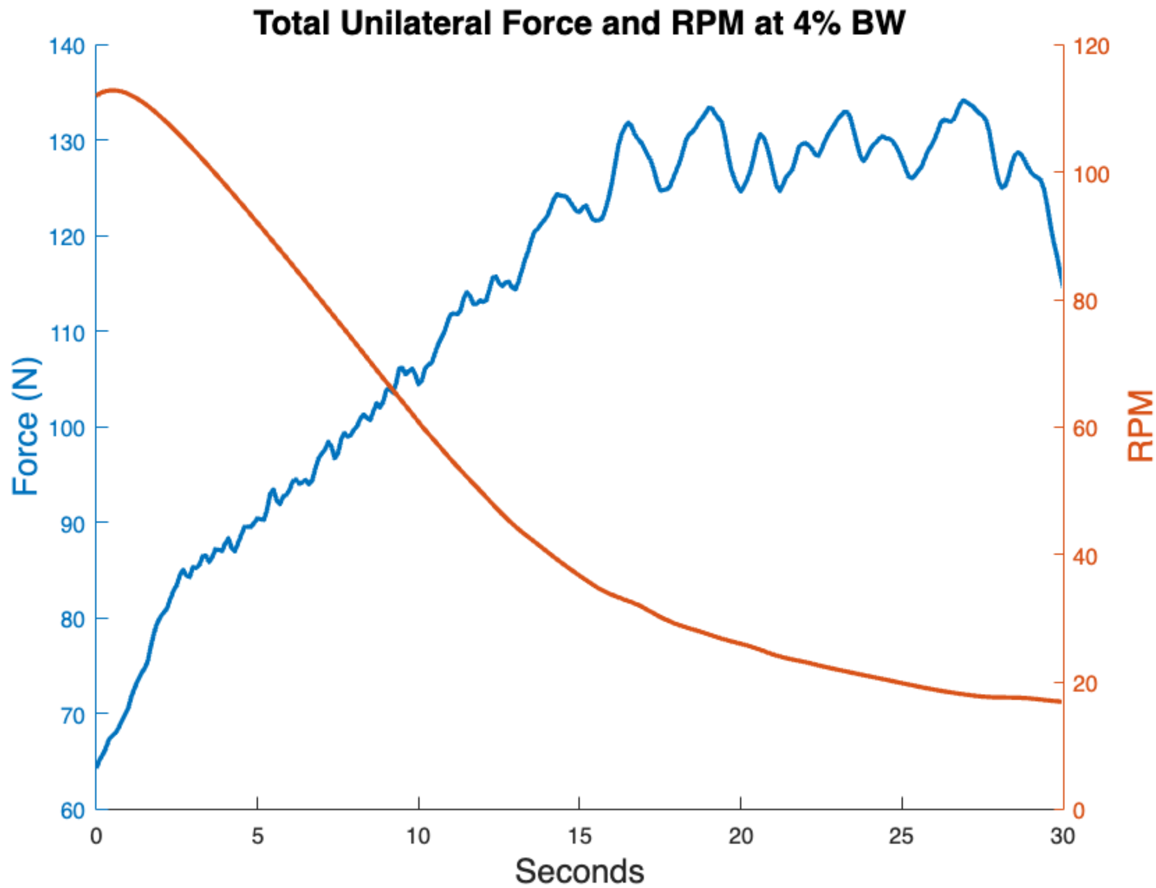
Total Unilateral Force and RPM at 3% BW
Force (N)
RPM
Seconds
130
120
110
100
90
80
70
60
120
110
100
90
80
70
60
50
40
30
0
5
10
15
20
25
30

Figure 12.



Total Bilateral Force and RPM at 4% BW
Force (N)
RPM
Seconds
125
120
115
110
105
100
95
90
85
80
75
130
120
110
100
90
80
70
60
0
5
10
15
20
25
30

Figure 13.



Total Unilateral Force and RPM at 4% BW
Force (N)
RPM
Seconds
140
130
120
110
100
90
80
70
60
120
100
80
60
40
20
0
0
5
10
15
20
25
30

Figure 14.

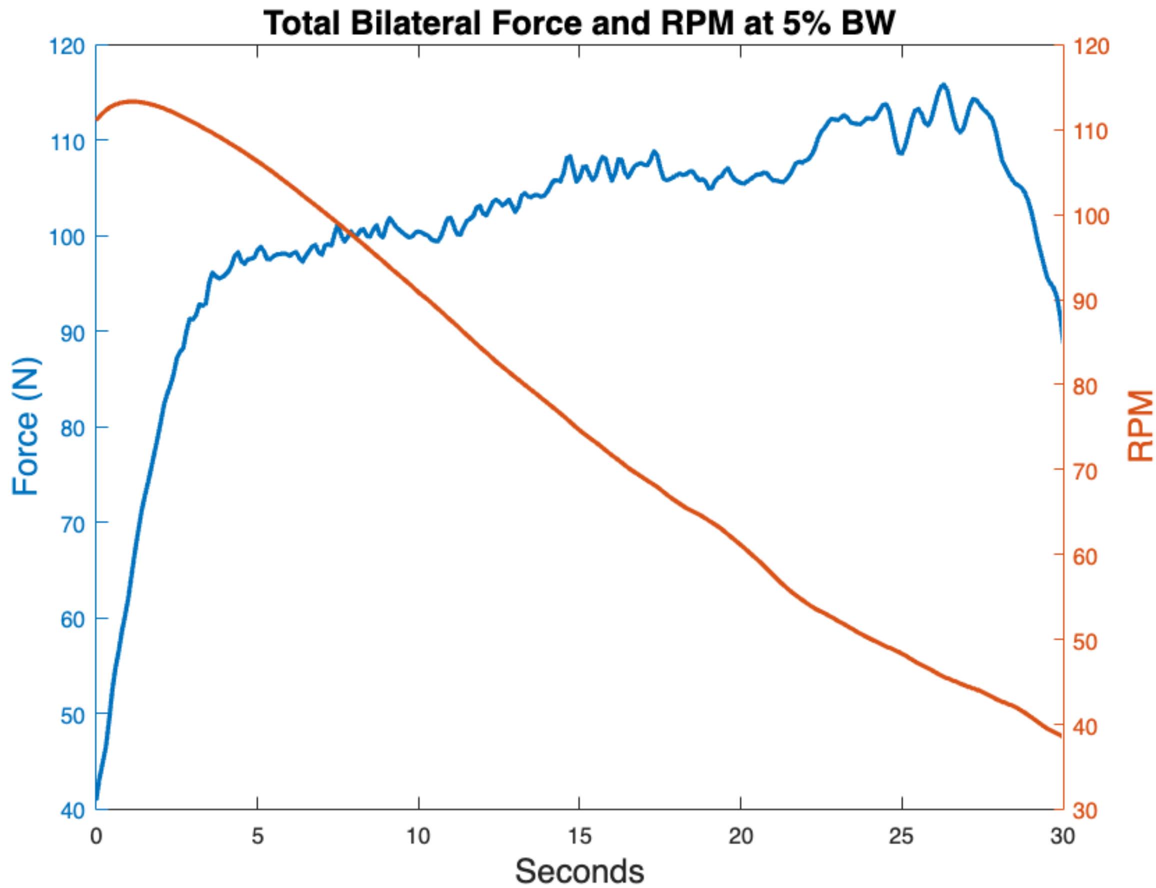
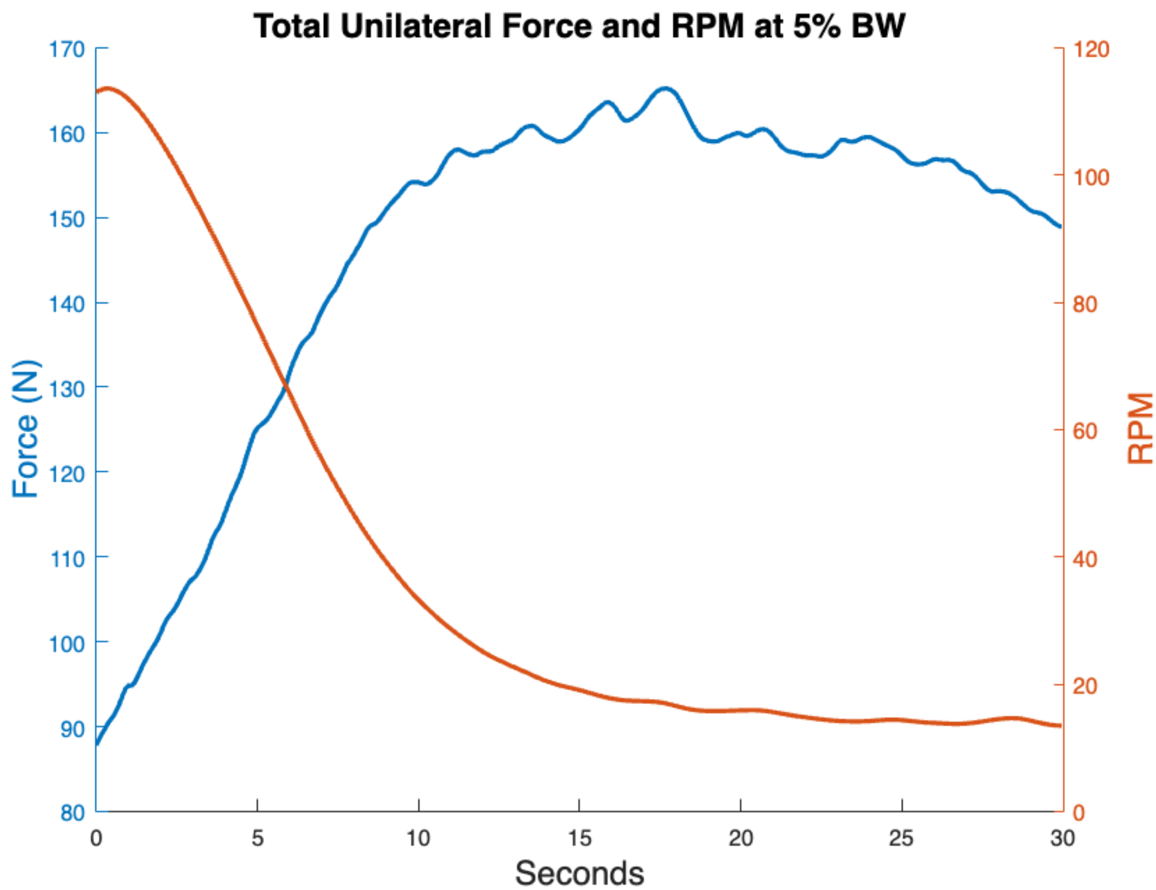

Total Bilateral Force and RPM at 5% BW
Force (N)
RPM
Seconds
120
110
100
90
80
70
60
50
40
120
110
100
90
80
70
60
50
40
30
0
5
10
15
20
25
30

Figure 15.


Total Unilateral Force and RPM at 5% BW
Force (N)
170
160
150
140
130
120
110
100
90
80
RPM
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Seconds

Appendix A: Free and Informed Consent Form

Informed Consent Form

Title:	Does a bilateral deficit exist in arm cycling and is it task-dependent?
Researcher(s):	Philip Edwards, Principal Investigator Memorial University of Newfoundland, pfedwards@mun.ca Shahab Alizadeh, Post-Doctoral fellow Memorial University of Newfoundland, shahab.a91@gmail.com Evan Lockyer School of Human Kinetics and Recreation, ejl006@mun.ca Angie Katherin Antolinez Romero, akantolinez@mun.ca School of Human Kinetics and Recreation Chris Edwards, cedwards19@mun.ca School of Human Kinetics and Recreation Jirho Ogolo, jaogolo@mun.ca School of Human Kinetics and Recreation
Supervisor(s):	Dr. Duane Button, PhD Human Kinetics and Recreation, Memorial University of Newfoundland dbutton@mun.ca, (709) 864-4886

You are invited to take part in a research project entitled:

"Does a bilateral deficit exist in arm cycling and is it task-dependent?"

This form is part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. It also describes your right to withdraw from the study. To decide whether you wish to participate in this research study, you should understand enough about its risks and benefits to be able to make an informed decision. This is the informed consent process. Take time to read this carefully and to understand the information given to you. Please contact the researcher, Philip Edwards, or Dr. Duane Button, if you have any questions about the study or would like more information before you consent.

It is entirely up to you to decide whether to take part in this research. If you choose not to take part in this research or if you decide to withdraw from the research once it has started, there will be no negative consequences for you, now or in the future.

Introduction:
This research is being conducted by Mr. Philip Edwards, a master's student at the School of Human Kinetics and Recreation at Memorial University of Newfoundland. The research team will consist of Shahab Alizadeh, a post-doctoral fellow, Evan Lockyer, a PhD candidate, and master's candidate Angie Katherin Antolinez Romero. As part of my (Philip Edwards) master's thesis, we are conducting research under the supervision of Dr. Duane Button, PhD.

The BLD phenomenon is characterized by a reduction in force from a single limb during bilateral actions when compared to the same action performed unilaterally. Bilateral deficit is a widespread phenomenon that extends across many motor outputs and populations. No study has assessed if BLD is present in arm cycling. Further investigation may improve our understanding of how the neuromuscular system works to produce bilateral and unilateral movements and if the BLD phenomenon is task-dependent.

Purpose of Study:

The primary purpose of this study is to determine if a bilateral deficit exists in arm cycling and to investigate what may be responsible for the phenomenon. The secondary purpose of the study is to determine if BLD is task-dependent.

What We Will Do in this Study:

You will be expected to come to PE 1011-B four times for approximately 1.5 hours each for a total of 6 hours. The first session will include 9, 3-second maximal isometric hand grip contractions; 6, 5-second maximal upper body isometric contractions; and 6, 5-second familiarization trials with arm cycling sprints. The next three sessions will include 3, 30-second maximal arm cycling Wingate's each, at 3%, 4%, and 5% of body weight using the subject's non-dominant arm, dominant arm, and both arms. sEMG data will be recorded from the biceps and triceps brachii muscles on both arms. The skin will be thoroughly prepared by removing hair (via a handheld razor) and dead epithelial cells (via abrasive gel) and sanitizing using isopropyl alcohol swabs to reduce the impedance for sEMG recordings. Slow motion video will be recorded from the front angle, and the right and left side of the participant to assess kinematics data.

Length of Time:
There will be four testing sessions with each session being approximately 1.5 hours for a total duration of 6 hours.

Withdrawal from the Study:
You will be free to withdraw from this study at any time, without explanation. To do so you simply need to inform the researchers and you will be free to leave the lab. For the PARQ+ participants are not required to disclose personal, sensitive, or identifying information; and that they only need to indicate if their responses suggest that they are ineligible to participate. You may request for the removal of your data until February 1st, 2023, the date upon which the data is expected to be analyzed, by contacting the primary investigatory at pfedwards@mun.ca and stating your desire to have your data removed. If you are a student, withdrawal from this study will not in any way, impact either your grade in a course, performance in a lab, reference letter recommendations and/or thesis evaluation.

Possible Benefits:
There are several possible benefits associated with participating in this study which include:
1) Education on how to properly perform arm cycling, and how to perform isometric contraction exercises.
2) Exposure to the research environment and a number of research techniques.

Possible Risks:
There are several minor risks associated with participating in this study which include:
1) Strain or soreness of the arm muscles.
2) High intensity exercise could also lead to some residual discomfort for 2-3 days after the testing however with those who partake in upper body strength training, this response is highly unlikely.
3) You will have electrodes placed on the front and back of your arms. These electrodes have an adhesive that tends to cause redness and minor irritation of the skin. This mark is temporary (usually fades within 1-2 days) and is not generally associated with any discomfort or itching.

To minimize risk, all high intensity contractions will be supervised by an investigator all of whom are trained in first aid and CPR. Additionally, numbers for emergency services will be on hand in case medical attention is necessary. We have provided you with the contact information of necessary facilities, should you experience any significant physical, cognitive, social, or emotional harm because of participation in this study.

University Counselling Centre
5th Floor University Centre, UC-5000
Memorial University of Newfoundland
St. John's NL A1C 5S7
Tel: (709) 864-8874
Fax: (709) 864-3011

Confidentiality:
Confidentiality is ensuring that identities of participants are accessible only to those authorized to have access. The ethical duty of confidentiality includes safeguarding participants' identities, personal information, and data from unauthorized access, use, or disclosure. Participant's data will be kept anonymous and confidential by way of a numeric code assigned to the data files in place of any identifiable information such as the name. The code will be assigned and known only by the primary investigator (Philip Edwards). Coded data will be stored in physical form and digitally in Dr. Button's locked office.

Anonymity:

Anonymity refers to protecting participants' identifying characteristics, such as name or description of physical appearance. Participation is this study is not anonymous, given the location of the laboratory (PE – 1011A) where various people who may be near the lab will likely see participants entering / exiting the lab. However, every reasonable effort will be made to ensure your anonymity. Your participation will not be made known to anyone except researchers who are directly involved in this study. Your identity will not be identified in any reports, conferences or publications without your explicit consent. A coded identification number will be used in place of your name on any documents or files that may be linked to your participation in this study, so that any data is not identifiable. All data will be collected independently and kept confidential by way of codes assigned to participants.

Recording of Data:

sEMG data will be recorded via electrodes on the biceps and triceps brachii muscles on both arms. Force data will be recorded from the load cells on each hand crank of the arm cycle ergometer using Powerforce software. Power data from the arm cycle ergometer will be recorded using Wingate software. Lastly, slow motion video will be recorded from three Go-Pro cameras to assess biomechanical data. All data will be documented on computer software in the laboratory and stored on a password protected computer.

Use, Access, Ownership, and Storage of Data:

A) All data will be stored in hardcopy and password-protected digital copy in Dr. Duane Button's office at Memorial University of Newfoundland. Consent forms will be stored separately from participant data in a locked cabinet in Dr. Duane Button's office. Data access will be limited to Dr. Duane Button and investigators. Data will be kept for a minimum of five years, as required by Memorial University's policy on Integrity in Scholarly Research.

B) The data collected because of your participation can be withdrawn from the study at your request up until the point at which the results of the study are expected to be analyzed (~February 1st, 2023). Requests for removal of data can be emailed to the primary investigator at pfedwards@mun.ca.

Reporting of Results:

Data potentially may be published in a thesis and online journal articles. Published data will contain no personally identifying information. Results of this study will be reported in written and spoken form (local and national conferences and lectures). Written forms will include Philip Edwards' Master's thesis, which will be made accessible to the public following its completion via the QEII Library at Memorial University via http://collections.mun.ca/cdm/search/collection/theses.

Sharing of Results with Participants:

Upon completion of the study, please ask any specific questions you may have about the activities you were just asked to partake in. If you wish to receive a summary of the results, then please indicate this when asked at the end of the form.

Questions:

You are welcome to ask questions before, during, or after your participation in this research. If you would like more information about this study, please contact:
Philip Edwards, pfedwards@mun.ca or Dr. Duane Button, dbutton@mun.ca.

The proposal for this research has been reviewed by the Interdisciplinary Committee on Ethics in Human Research and follows Memorial University's ethics policy. If you have ethical concerns about the research, such as the way you have been treated or your rights as a participant, you may contact the Chairperson of the ICEHR at icehr@mun.ca or by telephone at 709-864-2861.

Consent:
Your signature on this form means that:

- You have read the information about the research.
- You have been able to ask questions about this study.
- You are satisfied with the answers to all your questions.
- You understand what the study is about and what you will be doing.
- You understand that you are free to withdraw participation in the study without having to give a reason and that doing so will not affect you now or in the future.
- You understand that the data collected can be withdrawn from the study at your request up until the point at which the results of the study are expected to be analyzed (~February 1st, 2023).
- You understand that if you choose to end participation **during** data collection, any data collected from you up to that **point will be destroyed**.

By signing this form, you do not give up your legal rights and do not release the researchers from their professional responsibilities.

Your Signature Confirms:

☐ I have read what this study is about and understood the risks and benefits. I have had adequate time to think about this and had the opportunity to ask questions and my questions have been answered.

☐ I agree to participate in the research project understanding the risks and contributions of my participation, that my participation is voluntary, and that I may end my participation.

☐ A copy of this Informed Consent Form has been given to me for my records.

______________________________ ______________________________

Signature of Participant Date

Researcher's Signature:
I have explained this study to the best of my ability. I invited questions and gave answers. I believe that the participant fully understands what is involved in being in the study, any potential risks of the study and that he or she has freely chosen to be in the study.

______________________________ ______________________________

Signature of Principal Investigator Date

Upon the completion of this study, would you like a brief summary of its results? (Circle Answer)

If yes, please provide your email address below.

Yes No

Email address

Appendix B: Ethical Approval

MEMORIAL UNIVERSITY

Interdisciplinary Committee on Ethics in Human Research (ICEHR)

St. John's, NL Canada A1C 5S7
Tel: 709 864-2561 icehr@mun.ca
www.mun.ca/research/ethics/humans/icehr

ICEHR Number:	**20230904-HK**
Approval Period:	November 17, 2022 – November 30, 2023
Funding Source:	
Responsible Faculty:	Dr. Duane Button School of Human Kinetics and Recreation
Title of Project:	*Does a bilateral deficit exist in arm cycling and is it task-dependent?*
Amendment #:	***01***

December 19, 2022

Mr. Philip Edwards
School of Human Kinetics and Recreation
Memorial University

Dear Mr. Edwards:

The Interdisciplinary Committee on Ethics in Human Research (ICEHR) has reviewed the proposed additions for the above referenced project, as outlined in your amendment request dated December 15, 2022. We are pleased to give approval to collect slow motion video recordings from three angles using Go-Pro cameras, as described in your request and subsequent communication, provided all other previously approved protocols are followed.

The *TCPS2* **requires** that you **strictly adhere to the protocol and documents as last reviewed** by ICEHR. If you need to make any other additions and/or modifications during the conduct of the research, you must submit an Amendment Request with a description of these changes, for the Committee's review of potential ethical issues, before they may be implemented. Submit a Personnel Change Form to add or remove project team members and/or research staff. Also, to inform ICEHR of any unanticipated occurrences, an Adverse Event Report must be submitted with an indication of how the unexpected event may affect the continuation of the project.

Your ethics clearance for this project expires **November 30, 2023**, before which time you must submit an Annual Update to ICEHR, as required by the *TCPS2*. If you plan to continue the project, you need to request renewal of your ethics clearance, and include a brief summary on the progress of your research. When the project no longer requires contact with human participants, is completed and/or terminated, you need to provide an annual update with a brief final summary, and your file will be closed.

All post-approval ICEHR event forms noted above must be submitted by selecting the *Applications: Post-Review* link on your Researcher Portal homepage.

The Committee would like to thank you for the update on your proposal and we wish you well with your research.

Yours sincerely,

James Drover, Ph.D.
Vice-Chair, Interdisciplinary Committee on Ethics in Human Research

JD/bc

cc: Supervisor – Dr. Duane Button, School of Human Kinetics and Recreation