THE SCALING OF MOTOR OUTPUT IN RAPID ISOMETRIC CONTRACTIONS AND DYNAMIC AGILITY SUB-MOVEMENTS

by

Christopher Calabrese

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fulfillment of the requirements for the degree of Master of Science in Exercise Science

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Christopher Calabrese

Approved: ____
Christopher A. Knight, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
David Edwards, Ph.D.
Chair of the Department of Kinesiology and Applied Physiology

Approved: ____
William B. Farquhar, Ph.D.
Dean of the College of Health Sciences

Approved: ____
Louis F. Rossi, Ph.D.
Vice Provost for Graduate and Professional Education and
Dean of the Graduate College

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Signed: ______________________________

Christopher A. Knight, Ph.D.
Thesis advisor

I certify that I have read this thesis and that in my opinion it meets the academic and professional standard required by the University as a thesis for the degree of Master of Science

Signed: ______________________________

Jeremy R. Crenshaw, Ph.D.
Member of the thesis committee

I certify that I have read this thesis and that in my opinion it meets the academic and professional standard required by the University as a thesis for the degree of Master of Science

Signed: ______________________________

Jocelyn F. Hafer, Ph.D.
Member of the thesis committee

I certify that I have read this thesis and that in my opinion it meets the academic and professional standard required by the University as a thesis for the degree of Master of Science

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This study investigated the rates of force production and muscle activity in young adults during both isometric and dynamic conditions, aiming to extend the quantification of rate-scaling to whole-body agility-related movements. Twenty healthy participants, free of neurological disorder and musculoskeletal injury, and equally divided by gender were recruited. Participants performed various tasks involving isometric force pulses and dynamic agility sub-movements while muscle activity was recorded via electromyography (EMG) from the lateral gastrocnemius, tibialis anterior, soleus, and peroneus longus.

In the isometric force pulse protocol, the dominant foot of the subjects was secured in a custom force measuring device, and maximal voluntary contractions (MVCs) were recorded for normalization. Participants then performed rapid force pulses at varying percentages of their own MVC, with five sets of twenty pulses each. Dynamic tasks included lateral stepping, forward and backward stops, and a cutting task, all performed at three self-selected intensities. Ground reaction forces and EMG signals were synchronized and collected.

Results showed a significant positive relationship between peak rate of force development (RFD) and peak force across all tasks, with R^2 values ranging from 0.517 to 0.870. Linear regression models quantified these relationships, and all tasks demonstrated significant rate-scaling ($p < 0.001$). EMG measures of excitation were significantly

associated with peak RFD, indicating modulation of neuromuscular activity. While correlations between

task-specific RFD scaling factors and overall agility assessed by the Agility T-Test were not statistically significant, trends suggested moderate associations.

This research provides evidence of rate-scaling from ground reaction forces during simple change-of-direction tasks and highlights the modulation of neuromuscular excitation in response to varying force demands. These findings have implications for sports science, rehabilitation, and training, suggesting potential for dynamic task studies in at-risk populations to evaluate neuromuscular control and intervention efficacy.

Chapter 1
INTRODUCTION

1.1 Background

The ability to produce rapid movements is important throughout the lifespan, as it is a critical component to one's ability to prevent falls, make a quick directional change, or react to changing environments during exercise and sport. A model commonly used to study how the nervous system controls rapid movement is the volitional performance of rapid isometric contractions (brief force pulses). When healthy adults produce rapid isometric contractions, the time to reach peak force is remarkably consistent regardless of the size of the contraction. This occurs because neuromuscular control mechanisms and neuromuscular morphology together provide an integrated neuromuscular system that linearly scales the speed of the contraction with the size of the peak force. In other words, larger, rapid contractions have greater rates of force development (RFD) compared to smaller rapid contractions.

The slope of the linear regression of isometric RFD against peak force (PF) has been named the **rate of force development scaling factor (RFD-SF)** (1). The RFD-SF is an informative measure of neural control because healthy populations exhibit strong positive scaling with little unexplained variance (high R^2), whereas older adults (1), (2) and people with pathology (3), (4) exhibit departures from this scaling with meaningful effect sizes. While most of the scaling-related research has focused on rapid isometric contractions of the upper and lower extremity and single degree of freedom joint flexion/extension tasks, little is known about whether similar scaling is present in dynamic movements that are related to whole body mobility and agility ((4) see for drop jump conditions) ((5) see for review).

Agility is important for dynamic sport performance and involves the production of peak mechanical power across a range of submaximal force levels (e.g. low force - high velocity movements). The definition of agility includes a requirement for both a physical and a cognitive component, such as the execution of physical responses to changing environmental conditions (7). Agility involves the initiation of body movement, changes of direction, and rapid acceleration or deceleration. Although agility is less often considered outside of sport performance, it is gaining attention as an ability that is relevant to functional independence and cognition in older adult populations (8). However, there is little information available (5) about whether the robust scaling that occurs in rapid contractions at a single joint is evident in the rapid-whole body movements that contribute to agility. The quantification of such scaling is interesting because many of the rate-dependent actions that are important in activities of daily living exist in the low-to-moderate range of submaximal force and power and likely require precise control for successful movement outcomes.

1.2 Purpose of Study

Therefore, the goal of this study was to address this gap in knowledge about the scaling of rapid dynamic agility-related movements. The following aims were proposed.

Aim 1 was to determine whether peak rates of change in ground reaction forces scale with peak forces during rapid agility-related movements of different intensities or magnitudes (varied step size, cutting speed).

H1.1: The linear regression equations describing the relationships between rate and magnitude for each individual will have an average slope (RFD-SF) that is significantly greater than zero.

H1.2: The linear regression equations describing the relationships between the rate and magnitude for each individual will be characterized by an average R^2 that is greater than 0.5.

Aim 2 was to determine whether there are meaningful associations between the RFD-SF from isometric ankle plantarflexion and the RFD-SF from agility related movements.

H2.1: Isometric and agility-related RFD-SFs will be positively correlated.

Aim 3 was to determine whether measures of neuromuscular excitation rate (Q50B and rate of EMG rise, RER) scale with rates of force development across the levels of motor intensity (isometric contraction amplitude, step size or cutting speed) in the different tasks examined.

H3.1: The linear regression equations describing the relationships between rate of force development and neuromuscular excitation within subjects will be characterized by average slopes that are significantly greater than zero.

Aim 4 was to determine whether relationships exist between the measures of scaling and a timed test of whole-body agility.

H4.1: RFD-SF of the plantar flexors will be negatively correlated with Agility T-Test time.

This project will help us to understand neural control of rapid submaximal dynamic movements.

Chapter 2
METHODS

2.1 Protocol Overview

This study recruited 20 healthy young adults, evenly split between males and females, with an average age of 24.57 years and an average BMI of 24.1. Participants, free from neurological disorders or musculoskeletal injuries, completed various questionnaires to ensure eligibility. Exclusion criteria included any "yes" responses on the PAR-Q and a CAIT score below 27.5. The study focused on rates of force production and muscle activity recorded via electromyography (EMG) from the tibialis anterior, lateral gastrocnemius, peroneus longus, and soleus during isometric and dynamic conditions.

For the isometric force pulse protocol, each subject’s dominant foot was secured in a custom device, and MVCs were recorded for normalization. Subjects performed rapid force pulses at varying percentages of MVC, with five recordings of twenty pulses each. Whole-body agility-related movements were tested through lateral stepping, forward and backward stops, and a cutting task, each at three self-selected intensities. Ground reaction forces were recorded using a force plate, and EMG signals were synchronized and collected.

The Agility T-Test assessed overall agility, where subjects navigated a T-formation course as quickly as possible. Force data analysis focused on the relationship between peak force and the rate of force development (RFD), while rates of neuromuscular excitation were quantified using the rate of EMG rise (RER) and RMS amplitude (Q50B). For each individual subject, linear regression models were used to quantify relationships between RFD and peak force, as well as between EMG measures and RFD. Pearson's correlation coefficients and one-sample t-tests were used to test hypotheses regarding the scaling factors and associations across conditions.

2.2 Subjects

Twenty healthy young adults, including ten males and ten females were recruited to participate in this study (24.57 ± 2.56 years of age, 1.71 ± 0.07 meters tall, 70.6 ± 8.59 kg, 24.1 ± 2.63 BMI). The study was well-powered for the main hypotheses of interest. With 20 subjects, a one-sample t-test comparing the tested RFD-SF values against a null hypothesis of zero would be powered at 0.99 (hypothetical RFD-SF=3 and sd=2, α = 0.05) (9). Participants were free of known neurological disorders or musculoskeletal injury at the time of testing. Subjects filled out multiple questionnaires; the Physical Activity Readiness Questionnaire for Everyone (PAR-Q), the Cumberland Ankle Instability Tool (CAIT), the Waterloo Footedness Questionnaire, a Sport and Activity History Questionnaire, and the International Physical Activity Questionnaire short form (IPAQ-SF). The PAR-Q (10) form with any "yes" responses being considered an exclusion criterion. A CAIT score of under twenty-seven and a half out of thirty possible points was also used as an exclusion criterion. The main considerations here are the risks associated with the Agility T-Test (11), which is a maximal performance test. CAIT scoring yielded a subject mean of 29.65 ± 0.67 for both the right and left ankles, and the IPAQ-SF showed that the subject's exercised 4.05 ± 1.82 days per week.

2.3 Electromyography

Myoelectric activity was recorded from pre-amplified surface electrodes (MA-300, Motion Labs Systems, Lake Elsinore, CA, USA) during the isometric and dynamic rate-scaling conditions but not during the Agility T-Test. The skin above the tibialis anterior (TA), lateral gastrocnemius (LG), peroneus longus (PL) and soleus (SOL) was shaved and cleansed with ethyl alcohol. A pre-amplified double differential surface electrode was placed on the belly of each muscle to measure surface electromyogram (EMG) amplitude per SENIAM guidelines (12). Signals were bandpass filtered from 10-500 Hz. Electrode placements were maintained across isometric and dynamic testing conditions.

2.4 Rapid Isometric Force Pulse Protocol

Subjects were seated on the floor with their back to the wall, and a pad placed below their dominant leg to provide a comfortable position. Their dominant foot (determined by which foot the subject would kick a ball with) was strapped into a custom device (Figure 1) to measure force with a strain gauge force transducer (SM-100, Interface Inc., Scottsdale, AZ, USA) at a 110-degree ankle angle (20 degrees of plantarflexion). The force was amplified, and hardware filtered (low-pass, 50 Hz) in real time (Model SGA, Interface Force Inc., Scottsdale, AZ, USA).

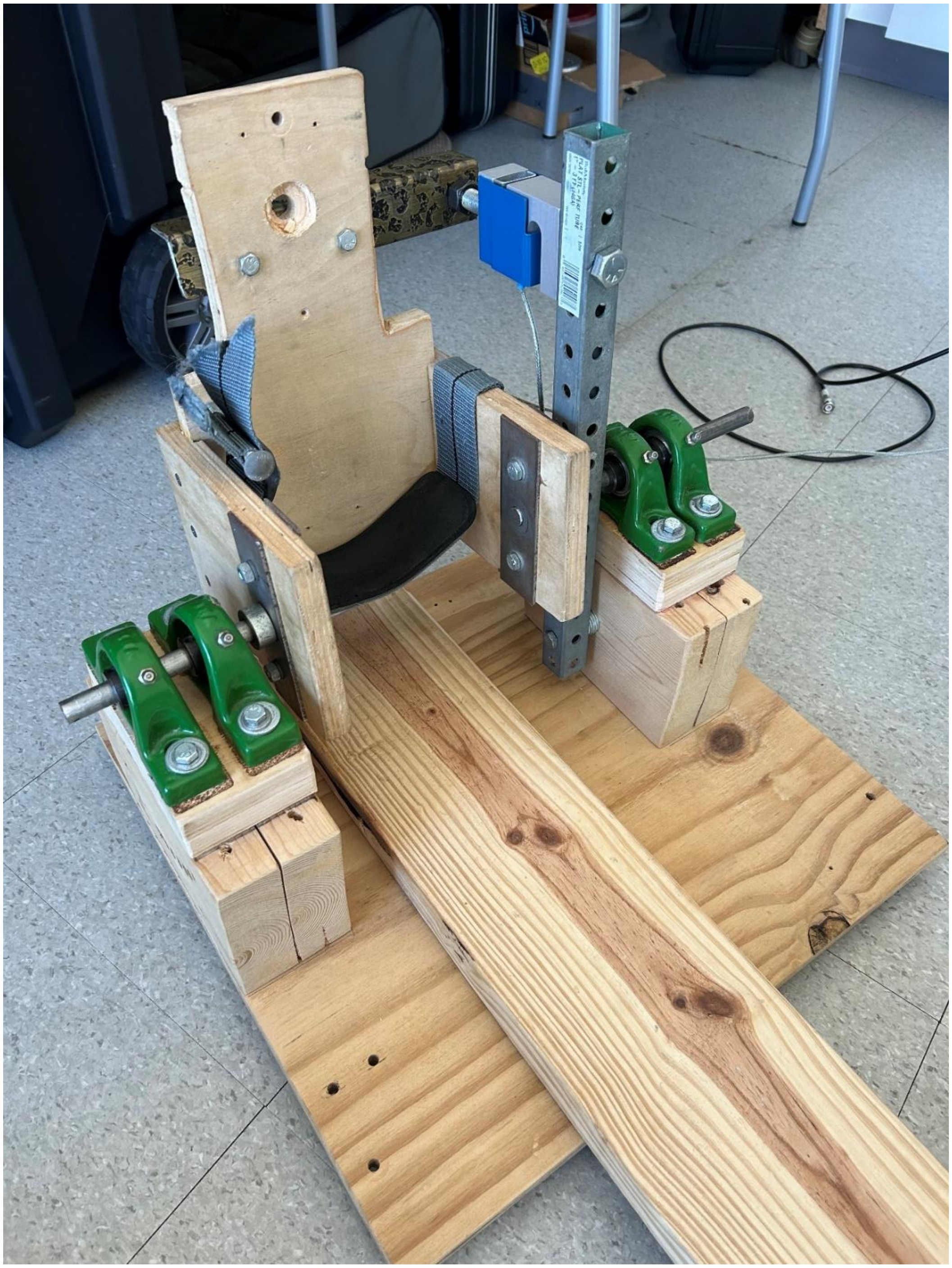

Figure 1. Isometric Force Pulse Device

Maximal voluntary contraction force (MVCs) was recorded for normalization purposes during three isometric contractions in ankle dorsiflexion and ankle plantar flexion, within the custom device. For the peroneus longus, three maximal ankle eversion contractions were performed against manual resistance applied by the investigator. Subjects were provided with 30 seconds of rest between MVC trials. The maximal force attained during the plantarflexion MVC trials was used to display relative force levels (%MVC) on a bar graph on a monitor positioned in front of the subject.

Following the MVC trials, the order in which the subjects completed the rapid force pulses was randomized using the "sample( )" function in R (R version 4.3.1, The R Foundation for Statistical Computing, Vienna, Austria). After a brief period where the subjects practiced the performance of rapid force pulses, five recordings of twenty force pulses were recorded. In each recording, subjects were instructed to produce five pulses to each 20%MVC, 40%MVC, 60%MVC, and 80%MVC. To promote most-rapid task performance, subjects were instructed to focus on their quickness more than on their accuracy (13).

In total, the isometric recordings provided 100 pulses of varied amplitudes for regression analysis for each subject. Following the methods of Howard et al. (14) pulses were excluded from analysis if (1) they were outside of the desired amplitude range, (2) they were not started from a stable baseline, or (3) force did not return to the baseline level. Force and EMG signals were digitized at 1 kHz using DasyLab software (Measurement Computing, Norton, MA, USA) and a National Instruments cDAQ system with modules 9178 and 9239 (National Instruments, Austin, TX, USA).

2.5 Agility-Related Movements Protocol

Subjects completed a series of four agility-related tasks during which the ground reaction forces of the change of direction step were recorded from a force plate. The order in which the subjects completed the agility-related tasks was randomized using “sample( )” function in R (R version 4.3.1, The R Foundation for Statistical Computing, Vienna, Austria). Participants performed each of the tasks described below at three self-determined magnitudes: small, medium, large (randomized order). Each recording included 10 steps in a magnitude condition. The recordings were separated by two minutes. Steps were excluded if the subject lost balance or did not properly hit the force plate. An improper hit of the force plate includes instances where the subject’s whole foot was not on the force plate. Appendix 2 contains the standard script used to instruct subjects. The investigator also provided demonstrations of each task.

The four tasks were:

1. Lateral Stepping – This task simulates a direction change in the frontal plane. The subjects were instructed to stand to the side of the force plate and told to bear the majority of their weight on their non-dominant leg. With each step initiated at their own pace, they stepped with their dominant foot onto the force plate and as quickly as possible returned to the initial upright stance position.

2. Forward Stop – This task simulates an anterior to posterior direction change. The subject was instructed to stand approximately one meter from the force plate, and with small, medium, and large intensities, perform a step that reversed forward momentum and returned them to the starting position as quickly as they can.

3. Backward Stop – This task simulates a posterior to anterior direction change. The subject was instructed to stand approximately one meter from the force plate, and with small, medium, and large intensities, perform a step that reversed backward momentum and returned them to the starting position as quickly as they can.

4. Cutting Task – The subject stood at a preferred distance, between 3 and 5 steps away from the force plate to perform rapid changes in running direction (cutting maneuvers). Subjects were instructed to strike the force plate with their dominant foot and make a 45-degree cut away from the dominant foot (e.g. strike with right foot for left cut). Subjects were instructed to approach the force plate at slow, medium, and fast speeds and to emphasize the explosiveness of the cutting step. Fast speeds were quick but not maximal. Blocks of ten cuts were completed at the subject's own pace, with two minutes between each recording. Signal Acquisition for Dynamic Tasks

Forces were recorded from a single force plate (AMTI Optima OPT464508-2000 9795M, Watertown, MA, USA) at a sampling frequency of 1.2 kHz. Recordings were low-pass filtered using a fourth order Butterworth filter with a 50 Hz cutoff frequency**.** Force and EMG recordings were synchronized and collected using Qualisys Track Manager software (Qualisys North America, Buffalo Grove, IL, USA).

2.6 Agility T Test

The agility T-Test was used to assess agility performance in all subjects (11). As shown in Figure 2, cones were placed in a T formation, with two cones (cones A and B) in a line ten yards apart from each other. Perpendicular to cones A and B, a cone (C) was placed to the left five yards away from cone B. Cone D was placed opposite cone C, five yards away from cone B. This created two ten-yard lines perpendicular to each other.

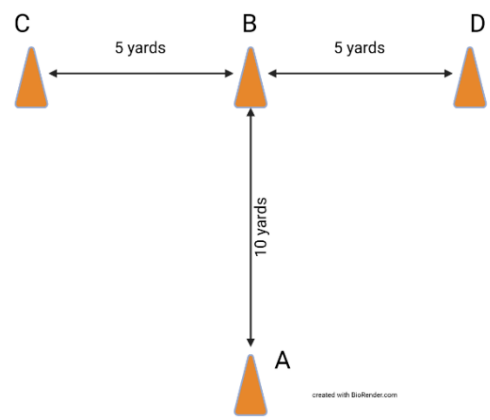

Figure 2. Agility T-Test Setup

After watching a demonstration of the task, subjects were instructed to complete the agility T-test as fast as they could. Cone A was considered the starting point, and each subject sprinted from cone A to cone B, where they rounded the cone, and shuffled without crossing their feet to cone C. They touched cone C and proceeded to shuffle without crossing their feet ten yards to cone D. They touched cone D, and shuffled without crossing their feet to cone B, where they rounded the cone and sprinted backwards to the finish line at cone A. The time taken to complete the agility T-test was measured with a stopwatch and the task was performed twice, with one minute between trials. The average of the trials was used for analysis in Aim 2.

2.7 Data Processing

EMG and force data was processed using R (R version 4.3.1, The R Foundation for Statistical Computing, Vienna, Austria).

2.7.1 Analysis of Force

Each discrete event of interest (isometric force pulses or steps in dynamic conditions, (Figure 3) was extracted from recordings for analysis. For simplicity, the term ‘pulse’ was used to describe the isometric and dynamic force events. The force variables of interest for each pulse were the peak amplitude of force and the peak RFD. The RFD time series was computed from the force recording using a moving slope function (15) with an overlapping 50 ms window (14). To determine the onset of the event, a force threshold of 9%MVC was used, to properly capture all deliberate force pulses and exclude all accidental forces. When force fell back below the threshold it was considered the end criteria of the force pulse. A linear regression of the peak RFD against peak force was used to calculate the RFD scaling factor (RFD-SF) which is the slope of the regression (1) and the corresponding R^2. For each of the dynamic conditions, the same analysis was applied to the resultant ground reaction force vector. While isometric forces were reported as a percent of MVC force (% MVC), and dynamic task forces were reported in Newtons (N), the resulting dependent measures that describe scaling (RFD-SF and R^2) are the dimensionless inverse second. All individual pulses and the resulting linear regression plots were visually inspected to locate and correct possible errors or outliers and to qualitatively evaluate the linearity of the relationships for each subject and task.

2.7.2 Analysis of Electromyograms

Electromyograms were line filtered at 60 Hz, then adjusted for gain, demeaned, full wave rectified and digitally bandpass filtered from 20-500 Hz using a Butterworth 4th order filter with a 20 Hz cutoff. In both isometric and dynamic tasks, rate of EMG rise (RER) was computed using a moving slope function (15) with an overlapping 50 ms window, within a region between the point 50 ms prior to force onset threshold (to account for electromechanical delay (16)) and peak force. For each pulse, root mean square (RMS) amplitude was computed over the period 50 ms prior to the peak RFD (Q50B) and the peak RER was computed within the window of time preceding peak RFD (17).

2.7.3 Statistical Analysis

All regression models and statistical tests were performed in R (R version 4.3.1, The R Foundation for Statistical Computing, Vienna, Austria).

2.8 Regression Models and Dependent Measures

This study was focused on the scaling of RFD and/or neuromuscular excitation with the size of most-rapid movements across a continuum of force levels. Linear regression was used to model all relationships between RFD and Peak Force and between EMG measures and peak RFD. Linear regression models were computed for each task examined within each subject and visually inspected for linearity and homoscedasticity.

The resulting regression slopes and R^2 values from all trials within each condition were treated as dependent measures that quantify scaling at the level of the individual.

2.9 Hypothesis Testing

The question addressed in Aim 1 was whether there is scaling between RFD and peak force obtained from a force plate during dynamic agility-related movements. Simple linear regression models were computed to describe the relationships between RFD and peak forces for each individual in each condition. A one sample t test was used to test the hypothesis of whether the mean of the scaling factors across RFD-SF from all trials of the like task differed from the null hypothesis of zero slope (RFD-SF=0, no scaling). For Aim 2 Pearson's correlation coefficient was used to determine the strength of associations among the individual RFD-SF values computed in isometric and dynamic conditions. With 20 subjects, correlation coefficients greater than r = .444 are considered significant at the 95% confidence level. In describing the magnitude of the correlations, we employ Cohen's conventions of 0.1-0.3 is small, 0.3-0.5 is moderate, and greater than 0.5 is large (18). For Aim 3, a simple linear regression model was used to describe the relationships between RFD and EMG measures (RER and Q50B) in each condition and muscle. As in aim 1, the slope from each the relationship was treated as a dependent variable for the individual and the one-sample t-test was again used to test the hypothesis that the average slope was greater than zero. In Aim 4, a Pearson's correlation coefficient was used to determine the strength of associations between the RFD-SF parameters from isometric and dynamic conditions and subject performance in the Agility T-Test. The same conventions as in aim 2 were used.

Chapter 3
RESULTS

3.1 Aim 1

Figure 3 (top) shows sample recordings from the isometric force pulse protocol and from the dynamic lateral stepping task. Note the manner in which the amplitude of the pulse or step change together with the corresponding peak RFD. Figure 3 (bottom) shows the corresponding linear regression plots for peak RFD and peak force for each pulse or step. These linear regressions provided the RFD-Scaling Factor (slope) and R^2 values to describe each subject's scaling of rate with amplitude. R^2 values ranged from 0.517 to 0.870 across the five tasks examined.

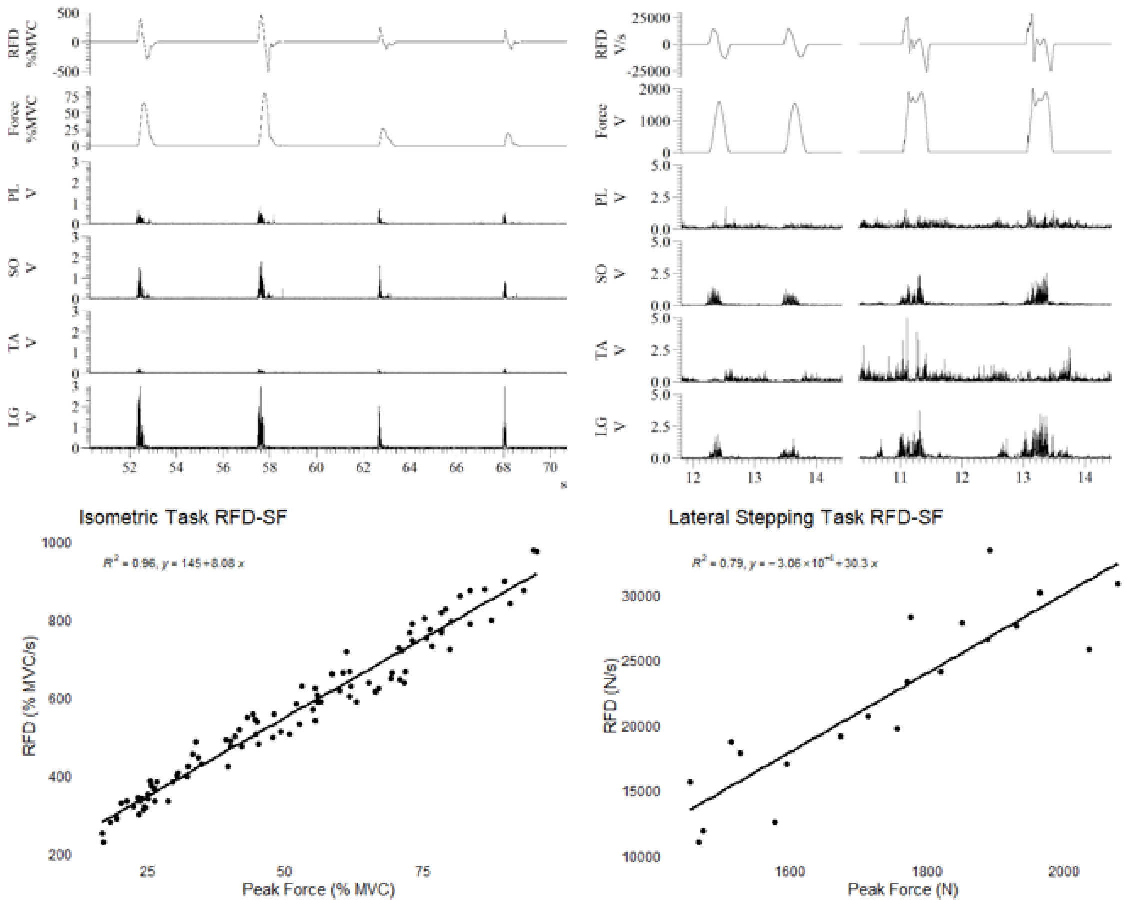

Figure 3. Sample recordings of small and large pulses in the isometric (top left) and dynamic lateral step (top right) conditions. Note that the peak RFD and Peak force covary in amplitude. Sample regression results for an individual subject in the isometric (bottom left) and dynamic lateral step (bottom right) conditions. The scaling of rate with pulse amplitude is demonstrated by positive regression slopes.

Table 1 provides the mean RFD-SF for each task with a 95% confidence interval and results from a one-sample t-test for a comparison with a null hypothesis of zero slope. All t-values supported a large effect size and all tasks had slopes that were significantly greater than zero ($p<0.001$). The corresponding R^2 values were moderate to strong for all tasks. Figure 4 presents the results of mean slope (RFD-SF) for each task completed by all subjects within the study.

Table 1. One-Sample t-tests for RFD-SF by task indicate that all conditions have significant rate scaling. R-square values for the dynamic tasks are all moderate and less than the R-square values from the better controlled isometric pulse condition.

Task	RFD-SF (s^{-1})	R-squared	SD	CV %	t-value	p-value
Isometric Task	9.6	0.87	2.2	22.7	19.7	< 0.001*
Cutting Task	20.6	0.77	5.6	27.1	16.5	< 0.001*
Lateral Stepping	15.7	0.77	7.7	49.0	9.1	< 0.001*
Backward Stop	10.2	0.52	5.3	52.4	8.5	< 0.001*
Forward Stop	23.8	0.63	8.9	37.6	11.9	< 0.001*

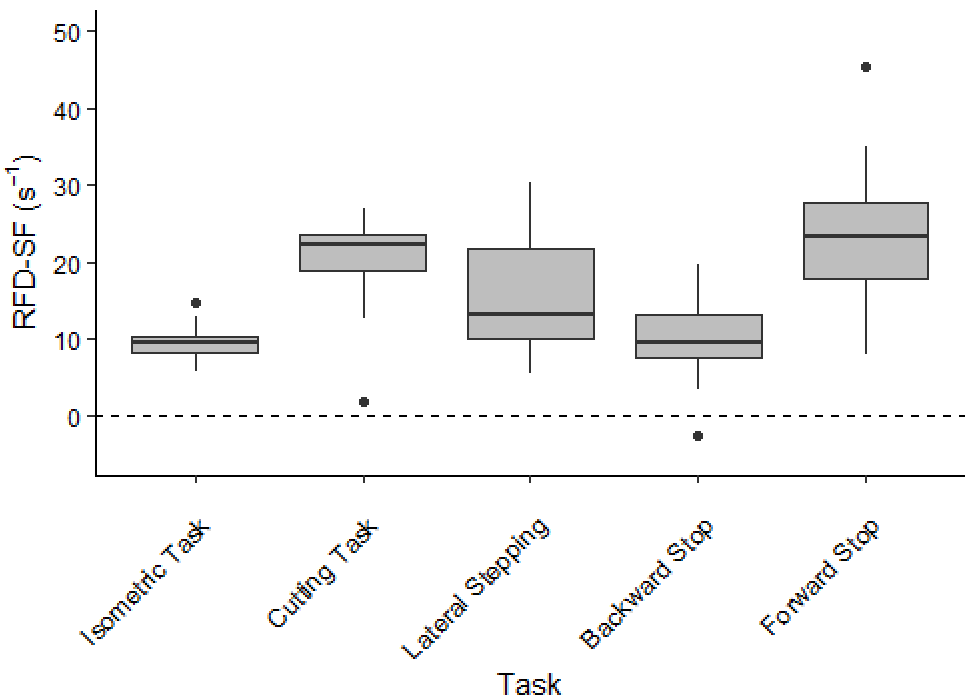

Figure 4. Mean RFD-SF for each task completed by all subjects within the study.

3.2 Aim 2

Table 2. Pearson's Correlation Matrix for RFD Scaling Factors Obtained from the Five Task Conditions.

Task	Isometric Task	Cutting Task	Lateral Stepping	Backward Stop	Forward Stop
Isometric Task	**1**	**0.02**	**0.11**	**0.26**	**0.25**
Cutting Task	0.02	1	-0.07	0.26	0.06
Lateral Stepping	0.11	-0.07	1	-0.01	0.42
Backward Stop	0.26	0.26	-0.01	1	0.32
Forward Stop	0.25	0.06	0.42	0.32	1

The correlation matrix presented in Table 2 illustrates the relationships between the scaling of rate with amplitude across the different tasks in the study. With a population of 20 subjects, none of the correlations reached the threshold for statistical significance (significance level of 0.05, critical r-value = 0.444). The forward stop and lateral stepping had a correlation of 0.42, the highest of the task correlations.

3.3 Aim 3

Tables 3-6 provide summary and inferential statistics for linear regression slopes between RFD and measures of muscle excitation (Q50B, RER) in the lateral gastrocnemius, tibialis anterior, soleus, and peroneus longus muscles, respectively, in each condition. For the lateral gastrocnemius (Table 3) mean regression slopes were all significantly different from zero (all $p < .012$), indicating associations between neuromuscular excitation and rate of force development. Coefficients of variation (CV) were computed for the purpose of comparing the relative variance in these slopes between individuals within each task. Lower values of CV indicate that subjects were more similar in the modulation of neuromuscular excitation to change peak RFD. For the tibialis anterior (Table 4), results were similar to lateral gastrocnemius except for the nonsignificant slopes for the RER in the Isometric Task and Q50B in the Cutting Task. For the soleus (Table 5), nine out of ten slopes were found to be significant, except for Q50B in the Backward Stop condition. For the peroneus longus (Table 6), all mean regression slopes were significantly different from zero, indicating associations between neuromuscular excitation and rates of force development. Figure 5 shows example relationships between neuromuscular excitation measures, Q50B and RER, and peak RFD in the isometric task and lateral stepping task.

Table 3. One sample t-test results for regression slopes in each task: lateral gastrocnemius.

Task	Parameter	Mean Slope	SD	CV %	t-value	p-value
Isometric Task	Q50B PeakRFD Slope	5.8	3.3	56.8	7.9	< 0.001*
Isometric Task	RER PeakRFD Slope	0.2	0.1	61.2	7.3	< 0.001*
Backward Stop	Q50B PeakRFD Slope	41.5	53.3	128.4	3.5	< 0.01*
Backward Stop	RER PeakRFD Slope	1.3	1.6	126.0	3.6	< 0.01*
Cutting Task	Q50B PeakRFD Slope	130.6	124.5	95.3	4.7	< 0.001*
Cutting Task	RER PeakRFD Slope	3.3	4.0	120.5	3.7	< 0.001*
Forward Stop	Q50B PeakRFD Slope	28.3	51.7	182.9	2.5	0.012*
Forward Stop	RER PeakRFD Slope	2.3	3.3	139.7	3.2	< 0.01*
Lateral Stepping	Q50B PeakRFD Slope	58.7	54.5	92.9	4.8	< 0.001*
Lateral Stepping	RER PeakRFD Slope	1.9	2.2	116.5	3.8	< 0.001*

Table 4. One sample t-test results for regression slopes in each task: tibialis anterior

Task	Parameter	Mean Slope	SD	CV %	t-value	p-value
Isometric Task	Q50B PeakRFD Slope	11.0	8.1	73.5	6.1	< 0.001*
Isometric Task	RER PeakRFD Slope	0.02	0.1	336.3	1.3	0.1
Backward Stop	Q50B PeakRFD Slope	23.5	26.7	113.7	3.9	< 0.001*
Backward Stop	RER PeakRFD Slope	0.7	1.0	149.7	3.0	< 0.01*
Cutting Task	Q50B PeakRFD Slope	21.0	60.5	287.5	1.6	0.1
Cutting Task	RER PeakRFD Slope	1.5	2.1	143.3	3.1	< 0.01*
Forward Stop	Q50B PeakRFD Slope	70.1	119.3	170.2	2.6	< 0.01*
Forward Stop	RER PeakRFD Slope	1.3	1.3	99.9	4.5	< 0.001*
Lateral Stepping	Q50B PeakRFD Slope	82.1	116.8	142.3	3.1	< 0.01*
Lateral Stepping	RER PeakRFD Slope	0.8	1.0	115.4	3.9	< 0.001*

Table 5. One sample t-test results for regression slopes in each task: soleus

Task	Parameter	Mean Slope	SD	CV %	t-value	p-value
Isometric Task	Q50B PeakRFD Slope	4.6	2.7	58.7	7.6	< 0.001*
Isometric Task	RER PeakRFD Slope	0.2	0.1	87.9	5.1	< 0.001*
Backward Stop	Q50B PeakRFD Slope	17.9	46.2	259.0	1.7	0.05
Backward Stop	RER PeakRFD Slope	0.7	0.9	128.1	3.5	< 0.01*
Cutting Task	Q50B PeakRFD Slope	127.3	154.6	121.4	3.7	< 0.001*
Cutting Task	RER PeakRFD Slope	2.1	3.2	152.8	2.9	< 0.01*
Forward Stop	Q50B PeakRFD Slope	38.9	84.9	218.3	2.0	0.03*
Forward Stop	RER PeakRFD Slope	2.3	2.3	99.0	4.5	< 0.001*
Lateral Stepping	Q50B PeakRFD Slope	76.3	105.2	137.9	3.2	< 0.01*
Lateral Stepping	RER PeakRFD Slope	1.5	1.4	93.1	4.8	< 0.001*

Table 6. One sample t-test results for regression slopes in each task: peroneus longus

Task	Parameter	Mean Slope	SD	CV %	t-value	p-value
Isometric Task	Q50B PeakRFD Slope	5.8	4.2	72.2	6.2	< 0.001*
Isometric Task	RER PeakRFD Slope	0.1	0.1	79.1	5.7	< 0.001*
Backward Stop	Q50B PeakRFD Slope	16.2	17.6	108.9	4.1	< 0.001*
Backward Stop	RER PeakRFD Slope	0.6	1.0	164.7	2.7	< 0.01*
Cutting Task	Q50B PeakRFD Slope	72.1	78.1	108.4	4.1	< 0.001*
Cutting Task	RER PeakRFD Slope	2.0	2.2	107.8	4.2	< 0.001*
Forward Stop	Q50B PeakRFD Slope	37.0	70.8	191.3	2.3	0.0152*
Forward Stop	RER PeakRFD Slope	1.4	2.7	184.5	2.4	0.0127*
Lateral Stepping	Q50B PeakRFD Slope	34.8	42.4	122.0	3.7	< 0.001*
Lateral Stepping	RER PeakRFD Slope	1.2	1.4	120.9	3.7	< 0.001*

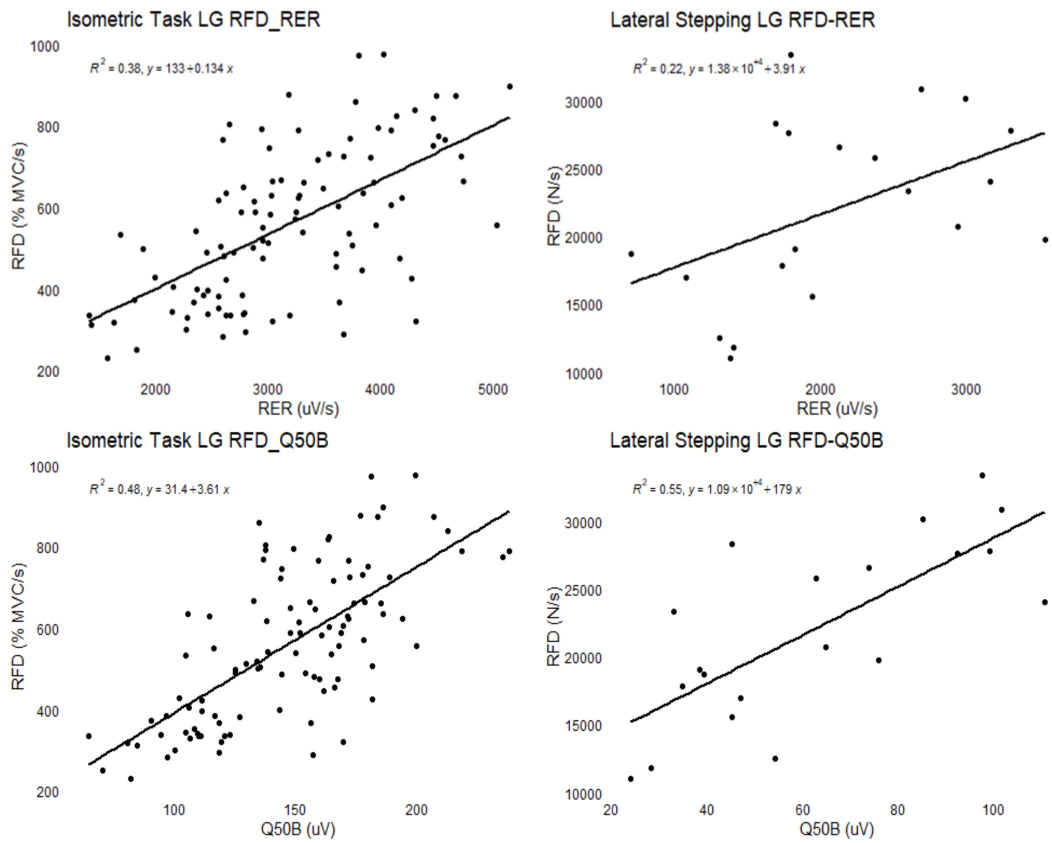

Figure 5. Example relationships between neuromuscular excitation measures (Q50B and RER) and peak RFD in the isometric task (left) and lateral stepping (right)

3.4 Aim 4

With 20 subjects, none of the Pearson's correlations between the Agility T-Test and RFD-SF values reached a critical r-value equaling 0.444 (Table 7). However, the forward stop task approached significance and correlations with isometric, forward stop, and lateral stepping were in range that may indicate a moderate association (18).

Table 7. Correlations between RFD-SF Scaling Factors Obtained from the Task Conditions and the Agility T-Test

Task	Isometric Task	CuttingTask	Lateral Stepping	Backward Stop	Forward Stop	Agility T-Test
Agility T-Test	-0.32	-0.15	-0.30	0.12	-0.42	1.00

Chapter 4

DISCUSSION

The main question addressed in this study is whether the rate-scaling that is observed in rapid isometric force production occurs in rapid whole-body movements that are contributors to whole-body agility. Aim 1 confirmed the presence of such scaling with significant RFD scaling factors in all three rapid stepping maneuvers and the cutting task. To elaborate on this finding Aim 2 examined possible correlations among the RFD-SFs from the five conditions tested under the premise that rate-scaling would covary across the 20 subjects such that subjects high or low scaling in one task would exhibit high or low scaling in the others, respectively. There were only a few moderate but non-significant correlations above $r = .3$ to support this idea. Aim 4 addressed the question of whether rate scaling in the isometric and dynamic tasks is related to performance of a whole-body agility test. Again, while not significant, three moderate correlations between scaling factors and the agility T-Test are interesting to consider. Aim 3 addressed the question of whether rates of neuromuscular excitation would be positively associated with rate of force development in the different tasks. Two measures of neural excitation (Q50B and RER), four dynamic tasks, and four muscles provided 32 regression slopes that were treated as dependent measures for individual subjects. Thirty of these 32 average slopes were significantly greater than zero. This provides abundant evidence that these measures of neuromuscular excitation are modulated to control rapid ambulatory movements of different sizes.

Aim one sought to assess the peak rates of change in ground reaction forces, and if they scaled with peak force during the rapid agility-related movements of different intensities. The isometric task exhibited a mean RFD-SF slope of 9.57, a lesser slope compared to each of the dynamic tasks (Figure 4). This magnitude is expected, as noted in other healthy population studies, the mean RFD-SF is just under 10.0 (1,5,6,19). Our results in the isometric condition are greater than the mean isometric plantarflexion RFD-SF of 6.0 ± 1.1 reported by Sarabon et al. (5). While the instructions were the same for the completion of the isometric task between the two studies, the testing position was different. Our study had subjects seated so that the ankle was at a 110-degree angle, whereas Sarabon had subjects seated with their knees and hips at a 90-degree angle. Another difference is that the subjects in our study had an average age of 24.7 ± 2.6 years old, whereas the Sarabon group had an average age of 15.1 ± 1.0 (5). It is known that adults have more developed muscular composition and power (20).

Our results from dynamic conditions were similar to the findings the Sarabon group in eccentric and concentric conditions. While our dynamic RFD-SF we were greater than those reported by Sarabon; 12.6 ± 2.2 and -11.3 ± 2.3, respectively (5), the greater slopes in dynamic tasks compared to isometric parallels the results of our study. At this early stage of extending the RFD-SF protocol to dynamic conditions, the similarities across different experimental settings are promising. Dynamic conditions may have greater scaling factors due to the involvement of multiple joints in power generation and the enhancement of force production that occurs through the stretch-shorten cycle

(21). The finding that mean RFD-SF was significantly greater than zero in all dynamic tasks adds strength to the study through internal replication. Each task required a unique motion of the body from relatively simple but quick stepping in three directions to a running cutting maneuver. The hypothesis that scaling would be present was supported for all conditions.

In aim 2, the correlations between scaling factors from different movements ranged from small to moderate in terms of effect size and with a sample size of 20 subjects, there were no statistically significant correlations. The finding that was most in-line with our hypothesis was the correlation of r = 0.42 between the forward stop and lateral stepping. Based on this and the other four correlations that were greater than r = 0.25 we maintain that scaling factors may be specific to the individual and correlated across tasks. Our rationale for this position is that the sample examined in this study may have been too homogeneous to provide meaningful variance in scaling factors. Indeed, the restricted range effect on correlation has been known for a long time (22) and may be overcome in future studies that examine these same correlations in young and older adults and possibly patients.

The same consideration can be applied to the small correlations between isometric and dynamic tasks by Sarabon (5). However, their healthy young sample provided a strong negative correlation of r = -0.837 between eccentric and concentric phases of a drop jump task (5). This makes sense as the concentric phase is directly influenced by the eccentric phase in this motion.

If one assumes that rate scaling at least partly determined by neural control, one would expect a scaled modulation of EMG measures of neural excitation. Two EMG measures, the rate of EMG rise and Q50B, were selected based on the work of Josephson et al (17) and computed from the electromyogram in the period immediately preceding peak RFD. While the distal lower extremity is not the only contributor to rapid whole-body changes in direction, distal muscles were selected for this study because the final expression of power during these dynamic movements is through the ankle joint (23). The vast majority of tests revealed moderate covariance between neural excitation and RFD. Together with the kinetic evidence of rate scaling in dynamic conditions (Aim 1) these EMG results are promising because the mechanistic information helps to validate the application of the scaling protocol developed in isometric conditions to dynamic tasks that may be more ecologically or functionally interesting. The logical expectation that isometric conditions would present less variance than dynamic conditions in the present work, is supported by the fact that the coefficient of variation for slopes reported in tables is consistently the least in isometric conditions (Tables 3-6), except for tibialis anterior which acts as an antagonist.

For the lateral gastrocnemius, significant differences were observed for Q50B and RER, supporting the scaled modulation of neuromuscular excitation. The magnitude of scaling can be compared across tasks within individual EMG measures. Using Q50B for example, the slope is greatest in the cutting task and least in the isometric task. One possible explanation is that while the isometric task requires no involvement of the LG for actions outside of pure plantarflexion, it would be largely involved in producing force eccentrically, concentrically and to control ankle motion in multiple degrees of freedom (24). The parallel pattern in RER adds logical validity to the findings.

The tibialis anterior exhibited scaled modulation of EMG measures in most but not all regression models. In the cutting task the mean Q50B Peak RFD slope was not significantly greater than zero. This may be due to the nature of the cutting movement. The task does not require significant dorsiflexion activity at the ankle, the primary action of the muscle. Since Q50B is the value of 50 ms before the Peak RFD, the significant differences observed in the forward stop and lateral stepping may be more related to the role of tibialis anterior (25) in joint stabilization.

The results from the soleus muscle are exciting because the manner in which they parallel the results from lateral gastrocnemius (across task) contributes to the logical validity of the protocol. Much like the lateral gastrocnemius, the soleus plays a critical role in the plantarflexion of the ankle joint, as the two work alongside each other. It is especially important in the propulsion of the body, providing power for push-off (26). We can see similar results, as the cutting task appears to have the largest Q50B vs, Peak RFD slope values for the soleus muscle showing a significant activation in the lead up to the peak rate of force development in the task.

The peroneus longus t-tests showed significant differences in every parameter across the spread of tasks. The peroneus plays several important roles at the ankle such as controlling eversion of the foot, assisting in plantarflexion, and importantly maintaining stability (27) during tasks much like the cutting task we studied. We can see Q50B Peak RFD slope values for the cutting task due to the importance of eversion control and plantarflexion that the muscle provides. Again, the consistent pattern across muscles of how EMG-RFD slopes change across conditions (isometric low and cutting high) is supportive of the hypothesized modulation of neuromuscular excitation as a part contributor to corresponding RFD-scaling factors.

Collectively, the results suggest that each studied muscle is similarly involved in the modulation of rate of force development based on the RFD-SF slopes significantly above zero. What may not be seen are the mechanisms at play at the knee and hip and contributions from differences in muscle fiber type and series elasticity. With RFD-EMG regression R^2 values that were meaningfully less than 1.0, much of variance in motor output was not explained by lower extremity EMG measures.

If rate-scaling is a neuromuscular mechanism with relevance to rate dependent mobility, one would expect to see correlations with whole-body agility performance. The Agility T-test was run as a measure of agility in the sample population. Our sample was a mix between low sport activity (exercising less than three days per week for 30 minutes plus) and recreational sport activity (exercising at least three days per week for 30 minutes plus), as defined by Pauole et al. in a study on the reliability and validity of the Agility T-test. Their findings were a mean Agility T-test of 13.55 ± 1.33 seconds for females and a mean of 11.20 ± 0.80 seconds in male subjects for the low sport group; for the recreational sport group females had a mean Agility T-test time of 12.52 ± 0.90 seconds and 10.49 ± 0.89 seconds in the male group (11). Our results fall right in line with the findings in the Pauole paper, as our females completed the Agility T-test in an average of 13.94 seconds and the males completed the Agility T-test in an average of 11.57 seconds. The addition of the Agility T-test to the correlation matrix was aimed to illustrate the relationship with the various other tasks within the study. While none of the correlations between RFD-SFs and the Agility T-test crossed the significance threshold equaling r = 0.444, some were moderate in magnitude. The forward stop task and Agility

T-test approached significance, a potential trend worth evaluating more in the future due to its proximity to the critical threshold. The lack of correlations may indicate that a more comprehensive set of tasks is needed to capture the full skills required for agility, due to the physical and cognitive nature of agility. However, much like the discussion of the aim two correlation matrix the sample population may be indicative of restrictive range (28).

Chapter 5

LIMITATIONS

One limitation in the present study could be the relatively homogeneous sample population, consisting of individuals free of chronic ankle issues, neuromuscular disorder and musculoskeletal injuries with most subjects living an active lifestyle. As discussed, this may have a restrictive range effect on the results and would need to include a more diverse population to thoroughly evaluate correlations in the future.

Chapter 6
CONCLUSION

This work extends the quantification of rate-scaling from isometric testing conditions to dynamic, whole-body agility related movements where little work has been done (5). These results provide evidence of rate-scaling from ground reaction forces obtained during relatively simple change-of-direction tasks. Consistent with expectations, EMG measures of excitation exhibited modulation that was associated with peak RFD. This research can have implications for various fields, such as sports science, rehabilitation, training, and optimization techniques. As the isometric studies have included at-risk populations such as people with multiple sclerosis, Parkinson's Disease and Stroke, there is good potential to study dynamic tasks in these populations. The quantification of rate-scaling, or its absence using small stepping maneuvers on a force plate could potentially provide information about the quality of neuromuscular control mechanisms and the efficacy of interventions.

Chapter 7

REVIEW OF LITERATURE

7.1 Relationship between Proposed Work and the Lab's Focus

Our research program examined the neural control of rapid, short-lasting muscle contractions, primarily using isometric conditions. Our scientific inquiry involved neuromuscular control mechanisms and how they change with age, pathology such as Parkinson's disease and with exercise interventions. One specific interest in of our work is how the rate of increase in force scales with the magnitude of muscle contractions across a wide range of submaximal force levels, resulting in times to peak force that are relatively invariant whether the contractions are small or large. To advance this line of inquiry about scaling, this thesis proposed new aims to determine whether such scaling exists in rapid whole-body movements that are part of rate dependent activities of daily living and high-level athletic performance.

7.2 The Context of Agility

The functional significance of submaximal fast muscle contractions can be considered within the construct of agility. The ability to perform fast whole-body movements in a complex and changing environment is important for some activities of daily living and sport. In sport science and practice, *maximal* power and its determinants receive much attention. However, many fast movements performed in sport are not produced at maximal force or velocity (Power = Force x velocity) but are still critical for success. Consider soccer. While actions such as brief sprints, direction changes and some kicks may approach the athlete's peak power capabilities, there are many other physical maneuvers that must be fast but are also far from the peak forces and velocities that the muscle, joint system or whole body can generate. For example, while approaching a key location to intercept an opponent, the soccer player might make several small but most-rapid changes in direction that are key for overall task success. In isometric conditions and controlled single degree of freedom movements (e.g., elbow extension), the rate of motor output is known to scale with the amplitude of the task across a wide range of submaximal efforts. However, little is known about whether such scaling is expressed in dynamic whole-body movements that are also submaximal but rate-dependent, such as sport-related cutting maneuvers that are small to medium in magnitude. It is also interesting to consider whether the ability to scale the rate and magnitude of these movements (or minimize variables like contact time) relates to task performance in a whole-body agility T-test. The purpose of this review was to summarize relevant literature on agility and to synthesize studies that may extend the concept of rate scaling from isometric contractions to simple dynamic conditions and ultimately whole-body cutting maneuvers.

7.2.1 Operational Definitions of Agility

At the time of their 2006 review, Sheppard and Young reported that there was no clear definition of agility in the sport science community. Agility was generally understood as a collection of physical abilities including rapid movement initiation, changes of direction and accelerations or decelerations. In this review, Sheppard and Young proposed a new definition of agility for sport as follows:

> “a rapid whole body movement with change of velocity or direction in response to a stimulus”

The authors further elaborate in a way that integrates both physical and cognitive processes:

> “To be considered an agility task, the movement will not only involve change in speed or direction, but must also be an open skill, wherein a reaction to a stimulus is involved and the movement is not specifically rehearsed.”

This cognitive response is seen in the recognition of a stimulus, reaction or execution of a physical response(7).

Agility should be distinguished as a separate entity from speed, as results of Horicka et al., 2014 suggest that agility is not an ability of speed. Where speed can be shown in reactions, acceleration and deceleration, agility also includes the perceptual components involved in sport that would be an unexpected, and changeable stimuli occurring in real time(29). Indeed, training studies have shown that the specificity of training is important; with agility and speed groups demonstrating different performance outcomes. Young, et al., completed a training protocol where 36 men (24 ± 5.7 years), with at least one year of experience in activities involving sprinting or change of direction completed 2 training sessions per week for 6 weeks. They were separated into control, agility and speed groups, where both the speed and agility groups completed various repetitive runs (20, 30 and 40 yards), at a specific % of their maximum speed, and where the agility group had added directional changes (either three, four or five) and a 100-degree directional change for each cut. The control group was able to continue their regular activities but instructed not to add any new training. Following the training period, the agility trained groups showed significant improvements relating to agility, whereas they produced a nonsignificant change in straight line sprint speed. Speed groups showed significant increases in straight sprint speed but no improvements in agility tasks. The training protocols exhibited high specificity with little transfer to the other task(30). One might therefore consider whether speed-focused exercise interventions in special populations with high fall risk are enough to improve population-appropriate agility function.

7.2.2 Change of Direction as a Component of Agility

Change of direction (COD) is an important component of agility. The velocity at which you approach the directional change and the angle of the change influence the COD intensity. Faster approaches to a COD and more acute angles of direction change both increase knee loading(31). More specifically, greater hip abduction occurs to generate greater medial-lateral forces alongside larger medial-lateral center of pressure and medial-lateral center of mass distances. However, this may elevate injury risk due to the generation of larger knee abduction moments because the resulting force vectors act more laterally relative to the knee joint center. The greater loads and elevated injury risk produce what some have called a “performance-injury conflict”(31). An athlete’s physical capacity can help to moderate this performance-injury conflict. Those with optimal mechanics are better able to endure higher loads(31).

Fuerst et al. completed a study that manipulated uncertainty in two different COD conditions. Thirteen amateur male basketball players (25 ± 3 years) participated in a study involving COD at the end of a straight six-to-eight-meter run. The three-by-three design included 3 cutting maneuvers and three different times at which a COD cueing light signal was presented. The cutting maneuvers were 1) COD of a sidestep 45 degree cut and 180 degree turns (performed by turning the left leg to the right or right leg to the left) and a crossover cutting mechanism. The crossover was included for reduced anticipation from participants and was not included in the analysis. In the three levels of the cueing factor, the light appeared early (900 ms before footstrike for the 45-degree cut and 1350 ms for the 180 degree turn), at a moderate time (700 ms before footstrike for the 45 degree cut and 1050 ms for the 180 degree turn) and late (600 ms before footstrike for the 45 degree cut and 900 ms for the 180 degree turn). The more challenging conditions with a later presentation of the light signal led to greater abduction moments, greater knee angles, and greater ankle inversion velocities. Together these spatial and temporal parameters increase the risk of ACL injuries and set the performance-injury conflict for the athlete(32). The authors suggested that COD under 90 degrees was velocity-dominant whereas anything over 90 degrees was force dominant. Velocity dominant CODs showed higher muscle activity at the knee, hip, and ankle joints due to the higher eccentric loading. This could be partially related to the shorter contract times in the velocity dominant CODs (33).

Each of these three studies also demonstrated that aspects of neuromuscular excitation (the timing and amplitude EMG) are sensitive to approach velocity, how sharp the turn is, and anticipation, where muscle pre-activation is a way to regulate stiffness of the joint prior to the movement. While the interest in this thesis is the broad construct of agility, the proposed experiments about rate scaling in agility sub-movements will not involve uncertainty. Therefore, the proposed study and its findings should be described as having a focus on components of agility.

7.3 Rate Scaling in Isometric Conditions

In the healthy neuromuscular system, there is a remarkably linear scaling of the rate of isometric muscle contractions with their amplitude. While muscle factors such as fiber type are likely contributors to this phenomenon, the rate of neuromuscular excitation is a major contributor with implications for health, human performance, pathology, and rehabilitation. The recent work in our lab, and now in labs elsewhere uses the slope of the linear regression between rate and magnitude to quantify this scaling in what is increasingly termed the rate of force development scaling factor (RFD-SF). There is an informative 2022 review on the scaling factor (6) and recent applications of this assessment of neuromuscular control include multiple sclerosis (3), jumping performance (5), and knee osteoarthritis (34), for example.

Table 8. Collection of Previous Study RFD-SF Results

Source	Population	Muscle Group	Action	RFD-SF	R2	Comment
Bellumori	Healthy Young Adult	Elbow Extensors	Extension	8.9 (0.7)	0.97 (0.05)	Day 1
		Index Finger Abductors	Abduction	8.2 (0.8)	0.97 (0.03)	Day 1
		Knee Extensors	Extension	8.3 (1.2)	0.96 (0.04)	Day 1
Sarabon	Healthy Young Adult	Ankle	Eccentric Phase	12.5 (2.3)	0.87 (0.09)	Drop Jump
		Ankle	Concentric Phase	10.9 (3.9)	0.80 (0.18)	Drop Jump
		Ankle	Ankle Plantarflexion	6.0 (1.1)	0.90 (0.06)	
Boccia	Amateur Runners	Knee Extensors	Extension	7.67 (1.88)	0.97 (0.02)	Pre Race
		Knee Extensors	Extension	7.74 (2.22)	0.96 (0.03)	Post Race
Howard	Parkinson's Disease	Index Finger Abductors	Abduction	3.90 (1.79)	0.43 (0.19)	
	Older Adult	Index Finger Abductors	Abduction	7.10 (2.64)	0.60 (0.14)	
Smalja	Healthy Adults	Knee Extensors	Extension	8.98 (1.1)	0.97 (0.02)	
Chou	Stroke	Ankle Dorsiflexion	Dorsiflexion	1.7	0.6	Paretic Limb
	Stroke	Ankle Dorsiflexion	Dorsiflexion	3.2	0.76	Non Paretic Limb

One of the earliest descriptions of how rate scales with the magnitude of isometric conditions was reported by Freund, et al in 1978. The authors suggest that the nervous system can modulate and scale the velocity of the contractions to its amplitude so that the contraction time remains constant. The study was performed on six healthy males aged 24-40 years old. The tasks performed on the first dorsal interosseous muscle, adductor pollicis, extensor or flexor indicis muscle, consisted of performing isometric contractions as fast as possible or hitting a target level as quickly as possible. The target force was presented on an oscilloscope throughout the trial. The main finding, replicated in subsequent studies, is that the rise time of quick voluntary contractions remains the same no matter how strong they are (35).

In neurologically intact healthy young adults this measure has very low variability, however as we age this becomes a sensitive measure especially to neurological diseases or impairments such as Parkinson's disease (14), multiple sclerosis

(3) or stroke (4). It has been seen that RFD-SF is not largely influenced by sex, with the assumption that RFD-SF is a property of neuromuscular control rather than differences in muscle mass or strength between genders (6). The effects of fatigue have also been noted as a non-issue, and while the protocol for obtaining RFD-SF is not fatigue inducing, one study compared the RFD-SF before and after a half marathon. In this study the RFD-SF of the knee extensors remained the same despite reductions in both maximal force production and maximal RFD (36).

7.3.1 Rate Scaling in Different Muscle Groups

RFD-SF has been assessed in many muscle groups including the ankle, elbow, knee, hip, wrist, and finger/grip muscles and it has been seen that with exception of the wrist and ankle muscle groups RFD-SF parameters are similar throughout the body. However, Smajla et al. recorded ankle plantarflexion RFD-SF with the knee bent at ninety degrees, thus invoking the slow muscle fibers of the soleus to produce most of the work (19). This could show a relation to muscle fiber type and RFD-SF in recordings.

7.3.2 Reliability of RFD-SF Parameters

The reliability of RFD-SF testing protocols has been reported as moderate to good with the likelihood that devices with proper fixation of the participant or with more force pulses collected to increase the reliability coefficient (1,14).

Looking specifically at some of the work from our lab, Bellumori et al. published a study that determined the number of pulses needed to compute a reliable RFD-SF. With over 50 pulses the results became reliable and were even more reliable with 100-125 pulses. The results showed that RFD-SF appears most reliable throughout all tested muscle groups when there are more than 75 pulses performed, with comparisons indicating no significant differences in RFD-SF between 75 (ICC = 0.83 for elbow extensors), 100 (ICC = 0.92 for elbow extensors) or 125 (ICC = 0.92 for elbow extensors) pulses. It was also determined that day did not have a significant effect on RFD-SF ($F_{1,14} = 1.47$, $p = 0.25$) (1). In addition to the RFD-SF, which is the slope of the linear regression between RFD and peak force, a measure that quantifies the variance in scaling is the R^2, the coefficient of determination. R^2 also showed no significant interactions between muscle groups and days, or between day and muscle. Thus, R^2 also appears to be a stable metric to quantify variability in the control of rapid muscle contractions across a wide range of submaximal force levels.

7.4 RFD-SF in Dynamic Conditions

Sarabon et al. (5), introduced the application of RFD-SF to a dynamic task, bilateral drop jumps. 55 young healthy adults took part in the study and after a 10-minute warm-up, they performed isometric plantarflexions against a dynamometer and drop jumps from different heights in random order. The plantarflexion MVCs and isometric RFD-SF protocol were completed while subjects were seated in a chair with the ankle, knees and hips set at 90 degrees. Sets of contractions were performed to a range of %MVC between 20 percent and 80 percent. Ten drop jumps were collected from heights (10 cm, 15 cm, 20 cm, 25 cm, 30 cm and 35cm). Subjects were instructed to step out from the box and land with short contact time, avoiding heels hitting the ground jumping as fast and high as possible. Significant moderate positive correlations were seen for the plantarflexion RFD-SF and eccentric phase drop jump RFD-SF ($r = 0.311$), while small negative correlations were seen between plantarflexion RFD-SF and concentric phase drop jumps ($r = -0.276$). This study is the first to use RFD-SF in a dynamic task and confirms that the ankle muscle group may have positive correlations between isometric and dynamic RFD.

7.4.1 The Influence of Accuracy on Rate Control

The rate of motor output is known to decrease when task requirements include the accuracy of pulse amplitude or displacement. Gordon and Ghez (13) discussed this in the context of the speed-accuracy tradeoff. As the protocol for obtaining RFD-SF requires the force pulses to occur as fast as possible the slope and variance of the RFD-SF relationship may be affected by accuracy requirements. However, the effect of accuracy on rate control has not been examined in the RFD-SF paradigm.

Gordon and Ghez compared the control of fast muscle contractions with instructions for either speed or accuracy (13). They examined elbow flexion force pulses matched to different pulse amplitudes and determined a speed-accuracy tradeoff exists within the two conditions in a way that fits the definition of Fitts' Law: the time it takes to move to a target is directly influenced by the distance to, and size of the target. The fast condition was described as making the force pulse as fast as possible and the accurate condition was to be as accurate as possible without caring about the time it takes to get there. With the accuracy condition, rise time (time from force onset to target) increased (i.e. slowing) whereas errors decreased as compared to the fast condition. Instructing the subject to produce force "as fast as possible" increased the amount of error consistent with the speed-accuracy tradeoff (13).

7.5 Rate Control of rapid single degree of freedom movements

Most studies on rate-scaling in dynamic tasks have used a single degree of freedom paradigm. In these studies, single degree of freedom involves the restriction of movement to a single joint and one plane. The advantage of examining control involving a single joint is that this reductionist approach simplifies the number of elements in the control problem of interest. These studies use movement in the horizontal plane to make the influence of gravity uniform throughout the range of motion.

In some clinical studies, information about normal control mechanisms can be found in the control subjects. In a study on Parkinson's disease by Berardelli et al. (year and reference here), eight neurologically normal individuals (mean age of 47 years old) performed rapid wrist flexion movements. Subjects were seated with their forearms strapped onto a platform allowing for only wrist flexion and extension motions in the horizontal plane. EMG was recorded from the flexor agonist and extensor antagonist muscles. Subjects were instructed to flex the wrist, starting position at 30-degrees of extension as rapidly as possible with either 15 or 60 degrees of displacement, and with or without a 2.2 Nm load. In normal subjects, the peak velocity was significantly faster in the larger 60-degree movements than the 15-degree no matter if the load was applied to the movement. This provides evidence of rate-scaling in dynamic conditions. An increase in movement amplitude was related to the size of the agonist burst and inversely related to activity in the antagonist group. The duration of these agonist bursts was constant with small movements under 30-degrees. However duration increased when either large movements were made, fatigue was present, or movements were performed with against the 2.2 Nm load (37).

In another clinical study on PD by Pfann et al. (38), nine neurologically healthy individuals (two women and seven men) performed a dynamic wrist flexion task. Subjects sat with their right arm abducted at 30 degrees and supported by a stationary platform. Their elbow was set into flexion at a 90-degree angle, with the wrist strapped into a splint that allowed motion to the horizontal plane. The position in which the hand was aligned with the forearm was defined as 0 degrees. The first task was to move to seven angles of flexion as fast as possible. Compared to the study by Berardelli above, the greater number of displacement conditions more completely described the scaling of velocity with amplitude, in which the larger amplitude displacements contained higher velocities. Agonist EMG activity again exhibited the same scaling with larger movements having higher EMG activity. This three-way relationship between amplitude, velocity, and agonist EMG activity connects the mechanical scaling with neural control. Scaling refers to the adjustment of movement parameters, such as speed and muscle activity, based on the task's requirements. In the context of this study, the observed scaling of velocity and EMG activity with amplitude indicates that the nervous system adapts its control strategies to optimize the efficiency and effectiveness of a given movement (38). By examining this relationship between amplitude, velocity, and muscle activity, researchers and practitioners can gain valuable insights into how the nervous system controls movements to achieve desired outcomes.

7.6 Regulation of Lower Limb and Joint Stiffness

The neural control of joint stiffness is a relevant consideration in agility as it relates to stability and responsiveness. The regulation of stiffness involves the contraction of involved muscles prior to footstrike. This prepares the musculoskeletal system for the act of directional changes and by stabilizing a joint, ideally prevents excess movements or extra rotations that could be detrimental to the joint and or body movement. Optimal regulation of stiffness can also help to maintain control of the body allowing for a stable base of support (39). Related to sport performance, optimal regulation of joint stiffness improves responsiveness, as this can allow for a quicker response in COD, and rapidly reacting to external stimuli.

7.7 The Stretch-Shorten-Cycle (SSC)

As we progress from isometric and controlled single degree of freedom dynamic paradigms to whole-body dynamic movements like hopping or cutting, one additional factor to consider is the involvement of the stretch shortening cycle (SSC). Komi et al., describe the stretch-shortening cycle as a sequence that occurs in muscles and tendons that contributes to force generation by utilizing elastic energy that is stored within the elastic elements of tendons and muscles. It begins with a rapid lengthening of the muscle-tendon unit, an eccentric phase, which stores elastic energy in the muscle-tendon unit – the stretch. This is followed by a transition from the eccentric to the concentric phase, where the stored energy is released as the muscles and tendons shorten generating a powerful force for explosive movements (21). The SSC has been extensively studied in running, jumping, and hopping, movements relating to agility. The SSC is known to enhance performance in dynamic activities as compared to comparable static actions.

Kubo et al., examined the effects of repeated SSC exercises on joint stiffness, with the goal to illicit fatigue and view changes in both muscle-tendon properties and EMG activity. After the fatiguing SSC exercise, ankle joint stiffness decreased by 20.7 percent. Neuromuscular activity did not decrease with this task, nor did the tendon stiffness. In both the 100 degrees per second and 250 degrees per second conditions (completed with a dynamometer), there was a similar decrease in active muscle stiffness, after repeated SSC exercises (39).

The significance of the SSC in the present work is that a key difference between scaling observed in isometric conditions and dynamic conditions will be that that latter involve the enhancement of motor output due to the SSC.

7.8 Plyometric Training

Studies on plyometric training are also related to the proposed thesis in that this practice is often intended to improve speed and agility and involves the SSC. Plyometric training is defined by exercises that include SSC movements. For the lower extremities, the training includes jumps, bouncing and hopping with body weight. Plyometric training has the ability to improve vertical jump heights in all four types of standard jumps: squat jump, countermovement jump, countermovement jump with arm swing, and drop jump. A review by Markovic et al. illustrated that jumps more closely related to SSC jumps, both countermovement jumps (countermovement jump and countermovement jump with arm swing), show greater positive training effects than in the other two jumps which use only concentric motions. Both athletes and non-athletes can show similar improvements with plyometric training with an observed effect between 4.7 and 8.7 percent (40).

The significance of plyometric training in the present thesis is that plyometric training or a history of such training has the potential to enhance both rate-scaling and agility.

7.9 Differences in Agility Performance

Fast and slow agility performance can be attributed to many factors; differences in approach; neurocognitive factors and physical characteristics. However, the neuromuscular activation strategy appears to be a key determinant. In a study where groups of “fast” and “slow” subjects were created based on their running time in a multidirectional agility testing (split by 50th percentile line), the “fast” group had a significantly greater peak force of the rectus femoris and vastus medialis muscles, as well as a significantly greater relative RFD at timepoints of 90 and 100 ms relative to the onset of a contraction (41). Results indicated that a greater rate of muscular activation and greater pre-activation provided better preparatory responses for the COD. Faster RFD is related to more efficient biomechanical movements, where greater knee and hip extension during the movement’s propulsive phase can lead to faster agility times. The “slow” group had a lower rate of EMG rise and reduction in the hamstrings to quadriceps activation ratio. This reduction reduces co-contraction not only increasing injury risk, but also decreases the amount of force produced within the motion thereby leading to slower agility times. As the results of the study showed, the “fast” group had significantly greater RFD, showing it may be a key determinant of agility performance. This would allow the group to produce greater force in a shorter period of time, thus allowing for quicker change of direction.

With 20 proposed subjects in this thesis, we looked for associations between the measures of rate scaling in the different experimental conditions and agility performance.

7.10 Exercise Training Improves Neuromuscular Excitation and RFD Scaling

Evidence of neural adaptations can be found in training studies that aimed to improve the rate of force development. A motor unit consists of a single motor neuron and the muscle fibers it innervates and is considered the most fundamental unit of force control. Doublets are a phenomenon in which two action potentials are produced by a single motor neuron with an instantaneous rate that far exceeds one that can be sustained throughout a muscle contraction. Doublets are typically defined as having intervals less than 5 ms (42). Doublets, and high initial motor unit firing rates in general, contribute to both a larger initial EMG signal and faster RFD. Van Cutsem et al., demonstrated that these doublets are trainable in healthy young adults. The authors used a training program that included training the dorsiflexor muscles of a singular leg for twelve weeks, with five sessions each week. Ten sets of ten dorsiflexion contractions against thirty to forty percent repetition maximum were completed each session. With a progressive overload training approach, there was a thirty-four percent increase in average load lifted after the training period. The training induced more doublets during the initiation of the movement. Comparatively, only 5.2 percent of recordings contained doublets pre-training whereas 32.7 percent of recordings contained doublets post-training. There was also a related 20% increase in total EMG activity in the initial stages of the contractions. This was quantified using the root mean square value of the electrical voltage recorded. Time to peak tension shortened by around sixteen percent while relative mean maximal rate of tension development increased around fifty-three percent. Those with more training may be more apt in agility or rapid movement tasks, due to the development of extra doublets and increased EMG activity overall and earlier on in the movement (42).

A soccer player who can produce doublets in their EMG signal, may have a better ability to modulate joint stiffness before footstrike and produce quicker bursts of motion against opponents. This may allow for more precise dribbling from an attacking player, able to keep the ball closer to their foot than the average defender can keep up with while trying to perform a tackle, as the doublets fire early in the movement providing the earlier burst. Very little is known about the scaling of doublets and neuromuscular excitation (summarized with multiple EMG measures) in rapid movements across a submaximal continuum of magnitudes.

Athletic history and/or rate-based training may provide greater neural resources that could enhance the scaling of submaximal dynamic movements. Surface EMG measures that quantify the early phase of muscle activation were proposed to explore these underlying mechanisms.

7.11 A Clinical Model: Joint Injury and Chronic Ankle Instability

While this thesis does not have a clinical focus, considering the potential implications of altered rate-scaling due to injury may be valuable. For example, control at the ankle joint is important for agility and it is known that joint effusion can alter the excitability of the motor unit pool, reflexes, and ultimately locomotor patterns in the soleus, tibialis anterior and peroneal muscle groups (43). This can also affect postural control as there is an increase in the motoneuron excitability in these muscle groups to protect the joint from further injury.

In a study in which the subjects were tested in a seated position with the knee flexed to 15 degrees and the ankle in a neutral position with the heel resting in a secure pad, a one millisecond square wave pulse was delivered to the sciatic nerve. There was an increase in the H-reflex and M-wave in all three muscle groups after a saline injection into the ankle joint space (simulating joint injury) (43). A subsequent study from the same group investigated the effects of joint effusion on a functional stepping task. Twenty neurologically sound individuals (21.9 average years of age, 10 male, 10 female), were asked to perform a resisted semi-recumbent stepping motion while seated in a dynamometer. To simulate an ankle joint injury, saline was injected into the ankle joint capsule. Impaired function was indicated by decreased plantarflexion torque and decreased EMG amplitude of the peroneal muscle group (44). Overall, these findings suggest that those with ankle injuries may not be able to perform at the highest level and could be at additional risk of another injury. The proposed thesis examines related neuromuscular control mechanisms in the specific context of rate control and scaling which could be a novel approach to the study of injury or swelling.

Chronic ankle instability (CAI) is a symptom of persisting pain and instability after a lateral ankle sprain. CAI is thought to develop due to improper care after a lateral ankle sprain. This specific type of ankle sprain is more common in sports that require rapid directional changes or jump-landing sequences. After the first occurrence of a lateral ankle sprain, there is a 70% chance that a second sprain may happen (45). 40% of individuals who have a second injury may develop CAI. The severity of CAI is assessed using the chronic ankle instability test (CAIT) (46). This is a subjective test that asks the subject to describe feelings of ankle pain, stability, and occurrences of "rolling" the ankle. Individuals with CAI often have changed biomechanics related to these feelings, whether consciously or unconsciously, and thus provide a difference in testing results from healthy young individuals. In a study completed by Simpson et al., there were large differences in the biomechanics of side-cutting tasks between healthy controls and those with CAI. Those with CAI had significantly greater ankle internal rotation between 35-54% of the stance phase and significantly greater tibialis anterior muscle activity at 86-94% of the stance phase. The fact there were significant effects in electromyography from the tibialis anterior supports our proposed use of these recordings in the present study. Furthermore, a more medial center of pressure positioning was seen in the CAI group from 81-100% of the stance phase (47). These changes may be a protective strategy to avoid recurrent injury due to the feel of the ankle giving way in those with CAI.

A study by Neptune et al. examined the role that the muscles crossing the ankle joint play in the coordination and stability of shuffle and 45 degree cutting movements. The gastrocnemius muscle (GAS) is important in transferring knee power to the ankle joint and activates before foot-strike during the shuffle movements. The GAS plantarflexes the foot before the impact is received and allows the peroneus longus (PL) and soleus to absorb the impact of the movement, reducing the load on the ankle joint. The PL also activates before impact and all three muscles were noted to provide a propulsion force before toe-off occurs. The PL is a critical muscle in preventing a lateral ankle sprain and consequently CAI, as it contributes to the stability of the subtalar joint as well as ankle plantarflexion. During the side shuffle, EMG activation occurs before touchdown and rises rapidly during the shuffle motion, slowing the supination of the ankle. This supination of the ankle remains relatively constant during midstance, and the PL activation remains high as a counter mechanism to balance the GAS, indicating that the PL stabilizes the subtalar joint as previously noted. The tibialis anterior (TA) function appeared differently for each motion in the side-shuffle and cut. During the shuffle, the TA dorsiflexes and supinates the foot after toe-off for the next cycle. During the cutting mechanism, the TA activity becomes constant through the movement to dorsiflex the foot before impact occurs. This presents a heel first landing and provides stability to the ankle joint (48). Much like the PL, the TA is critical in preventing lateral ankle sprains and eventually CAI, as in the cut mechanisms it prevents excessive plantarflexion at the ankle, a mechanism in ankle sprain injuries, and its pre-activation helps to stretch the soleus and GAS, reducing the joint load at impact. Overall, the TA had the highest sustained muscle activity at the ankle (49). In the proposed study, we similarly used electromyography to quantify the timing and amplitude of muscle activation in the gastrocnemii, tibialis anterior and peroneus longus muscles. The papers reviewed in the context of chronic ankle instability provide guidance for our research approach.

A study on volleyball players with functional ankle instability revealed that they may be predisposed to repetitive sprains due to reduced muscle activity specifically in the peroneus longus muscle. In the three studied muscles (TA, PL, and lateral gastrocnemius (LG)) the LG activated first and then the PL and TA followed. The unstable subjects showed LG and PL activation at the same time and then TA activation. As well as this, the PL showed lower muscle activation in the 50 ms window before impact in their lateral shuffling task (50). As noted by Neptune et al., the PL is the main ankle evertor and due to the weaker muscle activity, it may leave the unstable subjects prone to repetitive lateral ankle sprains (48). Although the proposed thesis does not directly examine CAI or re-injury, it is possible that a person's ability to optimally scale movement rate with its amplitude may be relevant. The proposed work is intended to advance scientific inquiry on rate scaling from primarily isometric studies into fast dynamic cutting maneuvers. The proposed work also tested the hypothesis that neuromuscular excitation will covary with the rate and amplitude of the tested movements (via surface EMG). Additional analysis will explore the timing of EMG relative to biomechanical landmarks such as isometric force onset or foot-strike in the dynamic tasks.

7.12 Agility T-Test

The agility T-Test is a change of direction test meant to simulate the movement of those in sport and has been shown as a reliable and repeatable method of assessing leg speed and COD. It has been shown to be dependable in assessing multiplanar movement. The test itself does not require much equipment and over three trials, the intraclass reliability of the agility T-Test was 0.98 (11) with a low standard error of measurement (51). All subjects in the proposed thesis performed the Agility T-Test as a whole-body measure of speed and agility.

7.13 Cumberland Ankle Instability Tool

The Cumberland Ankle Instability Tool is a questionnaire developed by Hiller et al., that allows for subjective grading of ankle joint instability. The questionnaire has nine questions and a 30-point scale on which it's measured. Likelihood ratios were calculated for groups of CAIT scores where scores of 27.5-30 have a 0.20 likelihood ratio to have a sprained ankle as compared to those without a history of ankle sprain, and due to this, a score of 27.5 was set as the threshold. The 24.5-27.0 group of scores have a ratio of 1.24 to have a sprained ankle compared to those without a history of ankle sprain. As the scores become lower, the likelihood of ankle sprains becomes exponentially higher. At the threshold score of 27.5, the sensitivity of the results is 82.9% and a specificity of 74.7%. At this score, the positive likelihood ratio is 3.27 and the negative likelihood ratio is 0.23. The study also evaluated the test-retest reliability of the questionnaire and found an intraclass correlation coefficients, model 2,1 of 0.96 (52), indicating very good test-retest reliability. Considering the potential effects of CAI on muscle activation in cutting maneuvers described above, the CAI was used as a screening tool to exclude individuals from study participation.

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APPENDIX

APPENDIX A. Verbal Instructions for Agility Sub-Movements

Task 1: Lateral Stepping

"You will stand to the side of the force plate with the majority of your weight on your non-dominant leg like so. You will perform ten small lateral steps with a medial return, then ten medium steps, and finally, ten large steps in separate trials. I'll demo each size now. Step with your dominant foot onto the force plate, and quickly return to the upright stance position limiting contact time. You'll have a two-minute break between each set. Any steps where you lose balance will be excluded."

Task 2: Forward Stop

"You will stand one meter from the force plate. Perform ten small, medium, and large steps with the goal of reversing your forward momentum as quickly as possible. I'll demo each size now. Making sure to have as little contact time as possible on the force plate, complete three trials for each intensity, with a two-minute break between each trial. Return to the starting position swiftly."

Task 3: Backward Stop

"You will stand about one meter from the force plate. Perform ten small, medium, and large steps with the goal of reversing your backward momentum as quickly as possible. I'll demo each size now. Making sure to have as little contact time as possible on the force plate, complete three trials for each intensity, with a two-minute break between each trial. Return to the starting position swiftly."

Task 4: Forty-Five Degree Cutting

"You will stand around one meter away from the force plate. Perform rapid changes in running direction (cutting maneuvers) with slow, medium, and fast approach speeds. Emphasize explosiveness in each cutting step. Perform ten forty-five degree turns at each approach speed for a total of 30 turns. Strike the force plate with your dominant foot and cut towards the opposite side. I’ll demo each size now. Slow will be akin to walking, medium will be like jogging and fast approach speed will be like sprinting. Complete the task at your own pace, returning to the start point before each cut, and you’ll have a two-minute break between each trial."

APPENDIX B. IRB/Human Subjects Approval

UNIVERSITY OF DELAWARE

Institutional Review Board
210H Hullihen Hall
Newark, DE 19716
Phone: 302-831-2137
Fax: 302-831-2828

DATE:	July 14, 2023
TO:	Christopher Knight, PhD
FROM:	University of Delaware IRB
STUDY TITLE:	[2068492-1] Quantifying Rapid Force Performance in Static and Dynamic Movements
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
EFFECTIVE DATE:	July 14, 2023
NEXT REPORT DUE:	July 13, 2024
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category (4,7)

Thank you for your New Project submission to the University of Delaware Institutional Review Board (UD IRB). The UD IRB has reviewed and APPROVED the proposed research and submitted documents via Expedited Review in compliance with the pertinent federal regulations.

As the Principal Investigator for this study, you are responsible for, and agree that:

- All research must be conducted in accordance with the protocol and all other study forms as approved in this submission. Any revisions to the approved study procedures or documents must be reviewed and approved by the IRB prior to their implementation. Please use the UD amendment form to request the review of any changes to approved study procedures or documents.
- Informed consent is a process that must allow prospective participants sufficient opportunity to discuss and consider whether to participate. IRB-approved and stamped consent documents must be used when enrolling participants and a written copy shall be given to the person signing the informed consent form.
- Unanticipated problems, serious adverse events involving risk to participants, and all non-compliance issues must be reported to this office in a timely fashion according with the UD requirements for reportable events. All sponsor reporting requirements must also be followed.

The UD IRB REQUIRES the submission of a PROGRESS REPORT DUE ON July 13, 2024. A continuing review/progress report form must be submitted to the UD IRB at least 45 days prior to the due date to allow for the review of that report.

If you have any questions, please contact the UD IRB Office at (302) 831-2137 or via email at hsrb-research@udel.edu. Please include the study title and reference number in all correspondence with this office.