Sprinting performance on the Woodway Curve 3.0™ is related to muscle architecture

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Abstract

To determine if unilateral measures of muscle architecture in the rectus femoris (RF) and vastus lateralis (VL) were related to (and predictive of) sprinting speed and unilateral (and bilateral) force (FRC) and power (POW) during a 30 s maximal sprint on the Woodway Curve 3.0™ non-motorized treadmill (TM). Twenty-eight healthy, physically active men (n = 14) and women (n = 14) (age = 22.9 ± 2.4 years; body mass = 77.1 ± 16.2 kg; height = 171.6 ± 11.2 cm; body-fat = 19.4 ± 8.1%) completed one familiarization and one 30-s maximal sprint on the TM to obtain maximal sprinting speed, POW and FRC. Muscle thickness (MT), cross-sectional area (CSA) and echo intensity (ECHO) of the RF and VL in the dominant (DOM; determined by unilateral sprinting power) and non-dominant (ND) legs were measured via ultrasound. Pearson correlations indicated several significant (p < 0.05) relationships between sprinting performance [POW (peak, DOM and ND), FRC (peak, DOM, ND) and sprinting time] and muscle architecture. Stepwise regression indicated that POWDOM was predictive of ipsilateral RF (MT and CSA) and VL (CSA and ECHO), while POWND was predictive of ipsilateral RF (MT and CSA) and VL (CSA); sprinting power/force asymmetry was not predictive of architecture asymmetry. Sprinting time was best predicted by peak power and peak force, though muscle quality (ECHO) and the bilateral percent difference in VL (CSA) were strong architectural predictors. Muscle architecture is related to (and predictive of) TM sprinting performance, while unilateral POW is predictive of ipsilateral architecture. However, the extent to which architecture and other factors (i.e. neuromuscular control and sprinting technique) affect TM performance remains unknown.

Keywords: Asymmetry, kinetics, assessment, power, technology

Introduction

Force and power production (from the lower limb) are influential of sprinting performance (Cronin & Hansen, 2005; Maulder & Cronin, 2005; Maulder, Bradshaw, & Keogh, 2006; Nesser, Latin, Berg, & Prentice, 1996). Recently, sprinting performance (speed, force and power), measured by the Woodway Curve 3.0™ non-motorized treadmill (TM; Woodway, Inc., Waukesha, WI), has been demonstrated to be predictive of 30-m sprinting performance (Mangine et al., 2014), and to provide a reliable assessment of maximal sprinting force and power (Gonzalez et al., 2013). The unique-curved design of the treadmill platform allows the runner to accelerate to full velocity, without the need of a restraining device. Though techniques appear similar to flat surface running, differences in locomotive kinematics (Snyder, Edlbeck, Myatt, & Reynolds, 2011), utilized musculature (Franks, Brown, Coburn, Kersey, & Bottaro, 2012), caloric expenditure (Snyder, Weiland, Myatt, Bednarek, & Reynolds, 2010) and velocity (Mangine et al., 2014) have been observed in comparison to motorized treadmills and flat-surfaced running. Thus it is possible that muscular characteristics, that are determinant of sprinting capability, may also vary during TM sprinting.

Within the locomotive musculature, sprinting performance is believed to be affected by the shortening velocity of the fibres (Abe, Fukashiro, Harada, & Kawamoto, 2001; Abe, Kumagai, & Brechue, 2000; Kumagai et al., 2000), which in turn is a
function of the biochemical activity (Bárány, 1967) and the architectural characteristics (Sacks & Roy, 1982) of the activated muscles. As such, investigations on the association between muscle architecture and sprinting performance have indicated that faster athletes possess greater thigh muscle thickness (Abe et al., 2001, 2000; Ikebukuro, Kubo, Okada, Yata, & Tsunoda, 2011; Kubo, Ikebukuro, Yata, Tomita, & Okada, 2011), longer muscle fascicles (Abe et al., 2001, 2000; Kumagai et al., 2000; Lee & Piazza, 2009) and smaller pennation angles (Abe et al., 2001, 2000; Kumagai et al., 2000) in comparison to slower athletes and age-matched controls. However, these data are limited to the isolated muscle regions in which they were collected and they do not account for muscle quality. Recently, Wells et al. (2014) reported variances in muscle thickness between muscular regions located laterally to each other within the same muscle (Wells et al., 2014). Consequently, muscular examination via cross-sectional area may be a more logical approach for defining these relationships. Furthermore, the echo intensity (ECHO) of contractile versus non-contractile components (muscle quality) within a specific area of muscle may be obtained simultaneously (Scanlon et al., 2014) and be reflective of the muscle’s force-producing capability. Moreover, differences have been noted in gait and muscle activation when comparing land versus treadmill locomotion (Sloniger, Cureton, Prior, & Evans, 1997; Stolze et al., 1997). Thus, it is unknown whether TM sprinting favours similar architectural characteristics as land sprinting.

Sprinting requires bilateral synchronization of muscular force and power to enable linear propulsion (McGinnis, 2013). Architectural asymmetry may be a vehicle that leads to unequal force and/or power development, as well as suboptimal sprinting performance (Bailey, Sato, Alexander, Chiang, & Stone, 2013; Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007; Newton et al., 2006; Savelberg & Schamhardt, 1995). Additionally, asymmetrical force and/or power production has been associated with injuries in sports (Schiltz et al., 2009; Shambaugh, Klein, & Herbert, 1991; Söderman, Alfredson, Pietilä, & Werner, 2001). Traditionally, force and power symmetry have been assessed via isometric, isokinetic and dynamic (i.e. vertical jump) tests (Schiltz et al., 2009; Shambaugh et al., 1991; Söderman et al., 2001), while architecture may be assessed by ultrasound (Abe et al., 2001, 2000; Ikebukuro et al., 2011; Kubo et al., 2011). However, the lack of specificity and potentially greater cost of testing equipment limits the practicality of these assessment tools. In contrast, a unique feature of the TM is its ability to measure sprinting power and force both unilaterally and bilaterally (Gonzalez et al., 2013; Mangine et al., 2014). It is possible that asymmetrical sprinting power and/or force, as measured by the TM, may be indicative of asymmetrical muscle architecture. Thus, the ability to screen for asymmetry while also measuring sports-specific sprinting power, force and speed is intriguing. Therefore, the purpose of the present investigation was to determine if previously reported relationships between muscle architecture and sprinting were consistent with sprinting performance (force, power and speed) on the TM. Since force and power are influenced by muscle architecture and its symmetry (Bailey et al., 2013; Impellizzeri et al., 2007; Newton et al., 2006; Sacks & Roy, 1982; Savelberg & Schamhardt, 1995), a secondary purpose was to determine if bilateral asymmetry in TM kinetics (force and power) was predictive of bilateral asymmetry in muscle architecture. Finally, in extension of that logic, a tertiary purpose of the study was to determine if TM sprint time was affected by the magnitude and/or asymmetry of sprinting kinetics (force and power) and muscle architecture.

Methods

The relationships between ultrasound measures of skeletal muscle architecture and sprinting performance, assessed by a 30-s maximal sprint on the Woodway Curve 3.0™ non-motorized treadmill (TM; Woodway; Waukesha, WI, USA), were examined in physically active men and women. Participants reported to the Human Performance Laboratory (HPL) on three separate occasions. On the first visit, eligible participants were advised of the purpose, risks and benefits associated with the study, followed by a familiarization trial on the TM. Previous research in our laboratory has indicated that one familiarization trial on the TM was necessary in order to obtain reliable measurements of peak power and force (Gonzalez et al., 2013). Within 1–2 days of the first visit, participants returned to the HPL. On this second visit, participants completed another 30-s maximal sprint on the TM. The final visit occurred within one week from the second visit and included ultrasound measures of the right- and left-leg thigh musculature in the HPL.

Subjects

A heterogeneous sample of 29 healthy physically active adults (men = 14, women = 15; age: 22.8 ± 2.4 years; body mass: 76.5 ± 16.3 kg; height: 171.4 ± 11.0 cm; %FAT: 19.5 ± 7.9%) were recruited to participate in this study. The Institutional Review Board of the University approved the research protocol. Subjects were asked to complete a health and activity questionnaire, Physical Activity
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Readiness Questionnaire (PAR-Q) and an informed consent prior to participation. All subjects were free of any physical limitations (determined by health and activity questionnaire) and had been recreationally active (i.e., participated in intramural sports and/or cardiovascular exercise in addition to resistance training 2–3 times per week). All participants had included some form of maximal sprinting into their exercise regimen over the past year.

**Descriptive measures**

Prior to physical exertion during the first visit, height (± 0.1 cm) and body mass (± 0.1 kg) were measured using a Health-o-meter Professional scale (Patient Weighing Scale, Model 500 KL, Pelstar, IL, USA). Calipers (Caliper-Skinfold-Baseline, Model #MDSP121110, Medline, Mundelein, IL, USA) were used to collect skinfold measurements (Triceps, Suprailiac, abdomen and thigh; Hoffman, 2006) and determine body fat percentage (%FAT) via previously published formulas (Jackson & Pollock, 1985).

**Maximal treadmill sprint testing**

Participants performed a 30-s TM sprint on the first and second visits, which were separated by 2 days, using previously described standardized procedures for measuring force and power (Gonzalez et al., 2013). Briefly, participants performed a 10-min warm-up consisting of 5 min on a cycle ergometer, followed by a 5-min walk (1.8 ms⁻¹) on the TM interspersed with 3–5 maximal sprints lasting 5 s. Following a 2-min rest, participants began one 30-s maximum effort sprint on the TM. Prior to maximal sprinting, all participants walked at a pace of 1.8 ms⁻¹ and were not allowed to accelerate. The study investigator provided a 5-s countdown and “Go” command. At “Go”, participants began a maximal effort sprint for 30 s. Participants were verbally encouraged throughout the sprint, but were not made aware of time remaining in the sprint. Maximal sprint trials were determined to be valid if the time to peak power (TPP) was achieved within the first 8 seconds (TPP = 1.82 ± 0.90 s; 0.09–3.69 s) of the 30-s maximal sprint (Mangine et al., 2014), otherwise they were excluded from statistical analysis.

All performance data from the 30-s maximal sprint were collected by a rotary encoder mounted on the rear shaft of the treadmill and analyzed by the manufacturer’s computer software (Pacer Performance System XPV7 2.1.07). The rotary encoder produces a digital pulse for every 2 cm of belt displacement in the horizontal plane. The Pacer software counts these pulses to generate displacement data which are then smoothed using a fourth-order Butterworth digital filter and differentiated using the finite difference technique to generate velocity data. Velocity data are then differentiated to produce acceleration data. Based on the known mass of the treadmill belt and measured frictional resistance, horizontal force is then calculated. Multiplication of force by velocity produces the power data. Vertical force was measured directly using four resistive strain gauges mounted directly underneath each corner of the treadmill belt support and sampled at 200 Hz.

From each valid trial peak sprinting power (POWPK), peak horizontal sprinting force (FRCPK), and sprint time at 10 m (TM10), 30 m (TM30) and 50 m (TM50) were used for statistical analyses. Additionally, unilateral measures of dominant leg average sprinting power (POWDOM), non-dominant leg average sprinting power (POWND), dominant leg average horizontal sprinting force (FRCDOM) and non-dominant leg average horizontal sprinting force (FRCN) were collected. All collected measures have been previously determined to be reliable following one familiarization trial (Gonzalez et al., 2013), while vertical force, mean sprinting power and sprinting time (>50 m) were necessarily excluded since they require a minimum of three familiarization trials. Leg dominance was determined as the greater value between right-and left-leg sprinting power (Kobayashi et al., 2013).

**Measurements of muscle architecture**

Non-invasive skeletal muscle ultrasound images were collected from the rectus femoris (RF) and vastus lateralis (VL), previously investigated in relation to sprinting ability (Abe et al., 2001, 2000; Ikubukuro et al., 2011; Kubo et al., 2011; Kumagai et al., 2000), using techniques previously described by our laboratory (Wells et al., 2014). Briefly, this technique uses sound waves at fixed frequencies to create in vivo, real-time images of the limb musculature. Participants reported to the HPL and were instructed to lay supine for 15 minutes to allow fluid shifts to occur before images were collected (Berg, Tedner, & Tesch, 1993). A 12-MHz linear probe scanning head (General Electric LOGIQ P5, Watertown, WI, USA) was used to optimize spatial resolution and was coated with water-soluble transmission gel and positioned on the surface of the skin to provide acoustic contact without depressing the dermal layer to collect the image. All measures were taken in both the RF and VL of both legs and performed by the same technician. The anatomical location for all ultrasound measures was standardized for each muscle in all participants. For measures of RF, the participant was placed supine on an examination table, according to the American
Institute of Ultrasound in Medicine, with the legs extended but relaxed and with a rolled towel beneath the popliteal fossa allowing for a 10° bend in the knee as measured by a goniometer (Bemben, 2002). For measures of the VL, the participant was placed on their side with the legs together and relaxed allowing for a 10° bend in the knee as measured by a goniometer. Following scanning, all images were analyzed offline using ImageJ (National Institutes of Health, Bethesda, MD, USA, version 1.45s), an image analysis software available through the National Institute of Health. For these analyses, a known distance of 1 cm shown in the image was used to calibrate the software program (Chapman, Newton, McGuigan, & Nosaka, 2008).

Measures of muscle cross-sectional area (CSA) and echo intensity (ECHO) were obtained using a sweep of the muscle in the extended field of view mode with gain set to 50 dB and image depth to 5 cm. For both muscles, landmark measurements were taken in the sagittal plane parallel to the long axis of the femur, while scanning occurred in the axial plane, perpendicular to the tissue interface. For the RF, scanning occurred at 50% of the distance between the anterior, inferior supraiaic crest and the proximal border of the patella. For the VL, scanning occurred at 50% of the distance from the most prominent point of the greater trochanter to the lateral condyle. Three consecutive images were analyzed and averaged using the polygon tracking tool in the ImageJ software to obtain as much lean muscle as possible without any surrounding bone or fascia for CSA (Cadore et al., 2012). The reliability of these measures was determined in the right limb of ten participants who returned to the HPL, approximately 24 hours after initial data collection, to repeat ultrasound scanning. The ICCs for RF CSA and VL CSA were 0.97 (SEM = 0.55 cm²) and 0.99 (SEM = 0.49 cm²), respectively. Concurrently, ECHO was determined by grayscale analysis using the standard histogram function in ImageJ (Cadore et al., 2012). ECHO in the measured area was expressed as an arbitrary unit (au) value between 0 and 255 (0: black; 255: white) with an increase in ECHO reflecting an increase in intramuscular connective tissue and adipose relative to lean skeletal muscle. ICCs were 0.93 (SEM = 3.80 au) for RF ECHO, and 0.96 (SEM = 2.26 au) for VL ECHO.

For both muscles, measures of muscle thickness (MT) were obtained from images, taken at the same site described for CSA, but with the probe-oriented longitudinal to the muscle tissue interface using Brightness Mode (B-mode) ultrasound (Cadore et al., 2012). Within each muscle, MT was measured perpendicularly from the superficial aponeurosis to the deep aponeurosis. Three consecutive images were analyzed and averaged offline (Thomaes et al., 2012). ICCs for RF MT and VL MT were 0.93 (SEM = 0.08 cm) and 0.98 (SEM = 0.03 cm), respectively.

Statistical analysis

Statistical package for social sciences software (SPSS; V. 20.0, SPSS Inc., Chicago, IL, USA) was used for all statistical calculations. Significant differences in sprinting kinetics (FRC and POW) and muscle architecture between the dominant (DOM) and non-dominant (ND) limbs were determined by a paired samples t-test. The relationships between muscle architecture and TM kinetics were assessed ipsilaterally and symmetrically via the calculation of Pearson product-moment correlation coefficients. The asymmetry between limbs was calculated as the absolute percent difference (%DIFF) between limbs. Subsequently, stepwise regression was used to determine if: (1) muscle architecture was predictive of sprinting kinetics (power and force); (2) asymmetry in sprinting kinetics (power and force) was indicative of asymmetry in muscle architecture; and (3) sprint time could be predicted by asymmetry in sprinting kinetics (power and force) and/or muscle architecture. All data have been expressed as mean ± standard deviation, where a criterion alpha level of \( p \leq 0.05 \) was used to determine statistical significance.

Results

For the 30-s maximal TM sprint, \( \text{POW}_{\text{PK}} \) (1104 ± 326 W), \( \text{FRC}_{\text{PK}} \) (292.8 ± 35.7 N) and sprinting time (TM10: 2.49 ± 0.27 s; TM30: 5.88 ± 0.75 s; and TM50: 9.19 ± 1.31 s) were collected for 28 participants; one female participant’s data were excluded (TPP = 26.8 s). No differences were observed between DOM and ND sprinting power 7.3 ± 5.7% (range: 0.4–17.9%) or sprinting force 8.1 ± 6.1% (range: 0.1–20.7%) (Figure 1). In terms of muscle architecture (Table I), a significant difference was observed between limbs for RF ECHO (\( p < 0.001 \)) and VL ECHO (\( p = 0.017 \)) No other differences were observed.

Sprinting kinetics

In terms of sprinting power, \( \text{POW}_{\text{PK}} \) was negatively related to RF ECHO\textsubscript{DOM} (\( r = -0.40, p = 0.034 \)) and the %DIFF in RF ECHO (\( r = -0.41, p = 0.029 \)). However, stepwise regression indicated the %DIFF in RF ECHO to be the best predictor for \( \text{POW}_{\text{PK}} \) (\( R^2 = 0.17, \text{SEE} = 302.8 \text{ W}, p = 0.029 \)). In the dominant limb, \( \text{POW}_{\text{DOM}} \) was positively related to RF (MT\textsubscript{DOM} and CSA\textsubscript{DOM}) and VL (CSA\textsubscript{DOM}) architecture, while it was negatively related to VL ECHO\textsubscript{DOM}. Of these variables, RF CSA\textsubscript{DOM} was
the best predictor for \( \text{POW}_{\text{DOM}} \) \( (R^2 = 0.61, \text{SEE} = 29.0 \text{ W}, p < 0.001) \) followed by \( \text{VL CSADOM} \) \( (R^2 = 0.67, \text{SEE} = 27.1 \text{ W}, p < 0.001) \), which improved predictive ability by approximately 5.2%. In the non-dominant limb, \( \text{POWND} \) was positively related to \( \text{RF MTND}, \text{RF CSA}_{\text{ND}} \) and \( \text{VL CSA}_{\text{ND}} \), with \( \text{RF CSA}_{\text{ND}} \) being the best predictor \( (R^2 = 0.46, \text{SEE} = 32.4 \text{ W}, p < 0.001) \), while \( \text{VL CSA}_{\text{ND}} \) improved predictive ability by 8.7%.

In regard to sprinting force, muscle architecture was not related to (or predictive of) \( \text{FRCPK} \) or \( \text{FRCDOM} \). However, \( \text{RF CSA}_{\text{ND}} \) was positively related to (and predictive of) \( \text{FRCND} \) \( (R^2 = 0.21, \text{SEE} = 4.80 \text{ N}, p = 0.015) \). The observed relationships between unilateral architecture and unilateral sprinting power/force are presented in Table II.

**Prediction of muscle architecture**

Sprinting kinetic asymmetry was not related to (or predictive of) architectural asymmetry. However, \( \text{POW}_{\text{DOM}} \) was significantly predictive of \( \text{RF MT}_{\text{ND}}, \text{RF CSA}_{\text{ND}} \) and \( \text{VL CSA}_{\text{ND}} \). \( \text{FRCDOM} \) was not predictive of non-dominant leg architecture nor could it significantly improve the predictability of \( \text{POW}_{\text{ND}} \). In the current sample, \( \text{RF ECHO}_{\text{DOM}} \) (DOM and ND), \( \text{VL MT}_{\text{DOM}} \) (DOM and ND) and \( \text{VL ECHO}_{\text{ND}} \) could not be predicted by TM sprinting kinetics. The ability of \( \text{POW}_{\text{DOM}} \) to predict dominant leg architecture and the ability of \( \text{POW}_{\text{ND}} \) to predict non-dominant leg architecture are presented in Table III.

**Prediction of sprint time**

\( \text{POW}_{\text{PK}} \) was negatively \( (p < 0.001) \) related to sprinting time at TM10 \( (r = -0.87), \text{TM30} \) \( (r = -0.88) \) and TM50 \( (r = -0.85) \). Similarly, \( \text{FRCPK} \) was also negatively related to \( \text{TM30} \) \( (r = -0.44, p = 0.019) \) and TM50 \( (r = -0.45, p = 0.018) \), but not TM10. \( \text{RF ECHO}_{\text{DOM}} \) was the only architecture measure significantly related to sprinting time \( \text{TM30} : r = 0.39, p = 0.040; \text{TM50} : r = 0.39, p = 0.038 \). Muscle architecture was not related to TM10.

Stepwise regression indicated that sprinting time \( \text{TM10, TM30 and TM50} \) could be significantly \( (p < 0.001) \) predicted by sprinting kinetics. The best predictor for TM10 was \( \text{POW}_{\text{PK}} \) \( (R^2 = 0.75, \text{SEE} = 0.14 \text{ s}) \), though the inclusion of \( \text{FRCPK} \) \( (R^2 = 0.80, \text{SEE} = 0.12 \text{ s}) \) improved predictive ability by 4.3%. \( \text{POW}_{\text{PK}} \) was also the best predictor for TM30 \( (R^2 = 0.78, \text{SEE} = 0.36 \text{ s}) \) and TM50 \( (R^2 = 0.73, \text{SEE} = 0.70 \text{ s}) \). However, the addition of \( \%\text{DIFF} \) in VL \( \text{CSA} \) \( \text{TM30} : R^2 = 0.83, \text{SEE} = 0.33 \text{ s}; \text{TM50} : R^2 = 0.78, \text{SEE} = 0.64 \text{ s} \) significantly improved predictive ability by approximately 4.1% and 4.7%, respectively.

When only muscle architecture was considered, stepwise regression revealed that \( \text{RF ECHO}_{\text{DOM}} \) was the best predictor for TM30 \( (R^2 = 0.15, \text{SEE} = 0.71 \text{ s}, p = 0.040) \) and TM50 \( (R^2 = 0.16, \text{SEE} = 1.22 \text{ s}, p = 0.038) \). Secondarily, the inclusion of \( \text{VL ECHO}_{\text{DOM}} \) improved the prediction of TM30 \( (R^2 = 0.35, \text{SEE} = 0.63 \text{ s}, p = 0.005) \) by approximately 17.4%

**Table I. Ultrasound measures of RF and VL architecture asymmetry**

<table>
<thead>
<tr>
<th></th>
<th>Dominant</th>
<th>Non-Dominant</th>
<th>Difference (%)</th>
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<tbody>
<tr>
<td><strong>RF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle Thickness (cm)</td>
<td>2.66 ± 0.35</td>
<td>2.66 ± 0.43</td>
<td>5.49 ± 5.61</td>
</tr>
<tr>
<td>Cross-Sectional Area (cm²)</td>
<td>16.7 ± 4.1</td>
<td>17.1 ± 5.3</td>
<td>10.41 ± 7.94</td>
</tr>
<tr>
<td>Echo Intensity (au)</td>
<td>60.8 ± 10.3</td>
<td>62.0 ± 9.9*</td>
<td>7.90 ± 6.93</td>
</tr>
<tr>
<td><strong>VL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle Thickness (cm)</td>
<td>1.87 ± 0.36</td>
<td>1.83 ± 0.39</td>
<td>10.75 ± 10.55</td>
</tr>
<tr>
<td>Cross-Sectional Area (cm²)</td>
<td>31.9 ± 8.8</td>
<td>31.9 ± 9.2</td>
<td>9.61 ± 9.08</td>
</tr>
<tr>
<td>Echo Intensity (au)</td>
<td>65.9 ± 11.8</td>
<td>67.5 ± 13.0*</td>
<td>8.69 ± 6.10</td>
</tr>
</tbody>
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*Significantly \( (p < 0.05) \) different from the dominant limb.
and TM50 ($R^2 = 0.32$, SEE = 1.12 s, $p = 0.007$) by approximately 14.8%. TM10 could not be predicted by muscle architecture alone.

**Discussion**

Our study appears to be the first investigation to examine the relationships between muscle architecture and sprinting performance on the TM. Previously, sprint training on the TM implied a greater emphasis on the quadriceps, in comparison to a flat, motorized treadmill sprinting (Franks et al., 2012). However, the exact relationships between the quadriceps and sprinting performance were not investigated. In this capacity, our data indicate that RF architecture (CSA & ECHO) is more important for TM sprinting than VL architecture; though VL CSA was still a strong predictor. This may be explained by the design of the TM and the manner in which sprinting performance was assessed. In general, the involvement of the RF coincides with increases in the speed of locomotion (Hernández, Dhaher, & Thelen, 2008; Nilsson, Thorstensson, & Halbertsma, 1985) and primarily during the recovery phase of a sprint; and to a lesser degree, during the flight phase when the remaining knee extensors assume control (Simonsen, Thomsen, & Klausen, 1985). Despite its involvement, however, RF architecture has not been shown to be as important to land sprinting as the remaining quadriceps muscles (Ikebukuro et al., 2011; Kubo et al., 2011). Thus it is possible that TM sprinting places a greater emphasis on leg recovery (compared to land sprinting), making it a useful tool for training this aspect of sprinting. Alternatively, our findings may be the consequence of differences in sprinting distance in comparison to existing data, which relate muscle architecture to 100-m sprinting (or 100 m sprinters; Abe et al., 2001, 2000; Ikebukuro et al., 2011; Kubo et al., 2011; Kumagai et al., 2000; Lee & Piazza, 2009). In the present investigation, peak force, power and sprint time represent performance occurring within a much shorter distance (0–50 m), which may be more indicative of acceleration ability (Cissik, 2010). Consequently, the observed relationships may be indicative of a greater RF influence within the first 50 metres of a sprint, but not necessarily beyond this point. In this case, a minimum of three familiarization trials may be necessary to determine if these relationships remain consistent beyond this distance (up to 100 m; Gonzalez et al., 2013).

The unilateral power generated during a sprint may be partially related to the architecture of the activated musculature (Bárány, 1967; Cormie, McGuigan, & Newton, 2011; Sacks & Roy, 1982). As a predictor for describing this architecture, our data indicate that the produced unilateral sprinting power ($POW_{DOM}$ and $POW_{ND}$) is capable of explaining 36–59% of the variance in measures of muscle size (Table III). Given that power is dependent upon force production, and therefore, the size of the activated musculature (Kraemer et al., 2002), this seems plausible. To a lesser degree, $POW_{DOM}$ could also predict VL muscle quality (ECHO). However, $POW_{DOM}$ could only explain 17% of the variance in muscle quality, which may be related to the measure (ECHO) itself, the participants’ physical activity and/or possibly gender. Echo intensity is considered to be reflective of both the contractile and non-contractile components (e.g. water and glycogen) of skeletal muscle, which are specifically reflective of an individual’s activity/training regimen (Scanlon et al., 2014; Tesch, 1988). Furthermore, men have been shown to possess greater absolute muscle quality (lower ECHO) in comparison to women, though not when normalized for body mass (Arts, Pillen, Schelhaas, Overeem, & Zwarts, 2010). Consequently, the heterogeneous nature of our sample in terms of gender and physical activity

| Table II. Bivariate relationships between unilateral measures of sprinting power/force and muscle architecture ($r$, $p$-value) |
|---|---|---|---|---|---|
| Dominant Leg | $POW_{DOM}$ | $FRC_{DOM}$ | $POW_{ND}$ | $FRC_{ND}$ |
| | RF | VL | RF | VL | RF | VL |
| Muscle Thickness (cm) | 0.73 (0.001) | -0.37 (0.055) | 0.28 (0.142) | -0.23 (0.235) |
| Cross-Sectional Area (cm$^2$) | 0.78 (0.001) | 0.11 (0.589) | 0.71 (0.001) | -0.45 (0.018) |
| Echo Intensity (au) | $-$0.37 (0.055) | $-$0.45 (0.018) | $-$0.23 (0.235) | $-$0.21 (0.289) |
| Non-Dominant Leg | $POW_{DOM}$ | $FRC_{DOM}$ | $POW_{ND}$ | $FRC_{ND}$ |
| | RF | VL | RF | VL | RF | VL |
| Muscle Thickness (cm) | 0.62 (0.001) | 0.33 (0.083) | 0.20 (0.311) | 0.30 (0.125) |
| Cross-Sectional Area (cm$^2$) | 0.67 (0.001) | 0.66 (0.001) | 0.45 (0.015) | 0.22 (0.256) |
| Echo Intensity (au) | $-$0.27 (0.173) | $-$0.30 (0.122) | $-$0.12 (0.551) | $-$0.07 (0.724) |

$POW_{DOM} = $ Dominant leg sprinting power; $POW_{ND} = $ Non-dominant leg sprinting power; $FRC_{DOM} = $ Dominant leg sprinting force; and $FRC_{ND} = $ Non-dominant leg sprinting force.
may have reduced the predictive ability of this particular measure.

As for architectural asymmetry, our data cannot support the use of asymmetrical sprinting kinetics (on the TM) to identify asymmetric architecture, despite the influence of asymmetrical architecture on sprinting power. Theoretically, asymmetrical architecture may cause the force production capability between legs to vary. During a maximal sprint, the imbalanced bilateral force contribution may result in sub-optimal magnitude or direction of linear sprinting force/power (McGinnis, 2013; Savelberg & Schamhardt, 1995). In support, asymmetrical muscle quality (RF) negatively influenced peak sprinting power. Ultimately, however, neither this imbalance nor the significant difference in VL ECHO affected sprinting time. It is possible that such imbalances are accounted for by the manner in which these muscles are recruited. Previously, it has been demonstrated that a physiological weakness in sprinting may be compensated for by a physiological strength (Fuchs, 1995). Since the TM is belt-driven, the dominant limb might be able to provide a greater contribution, indicated by the stronger relationships observed in the dominant limb, without affecting sprinting direction. Additionally, the synchronized recruitment of the active musculature may also disguise the weaknesses of an inferior limb (Mellor & Hodges, 2005; Semmler, 2002). Alternatively, the observed architectural asymmetries (5 – 11%) may not have been large enough to significantly affect TM sprinting time. Nevertheless, architectural asymmetry does not appear to have an overwhelming impact on TM sprinting performance, within the first 50 metres. Consequently, the influence of muscular activation should be investigated to examine these hypotheses.

Typically, faster sprinters possess greater force and power capability (Cissik, 2010). Our data suggest the same as TM sprint time was best predicted by peak force and power. When architecture alone was considered, ECHO DOM (RF and VL) was the best predictor for sprint time (TM30 and TM50). Given that greater muscle quality would suggest reduced impedance, from non-contractile tissue, for muscle recruitment (Goodpaster, Kelley, Thaete, He, & Ross, 2000), as well as greater strength and power (Cadore et al., 2012; Fukumoto et al., 2012), this too was to be expected. Interestingly, however, muscle size was not directly related to TM sprinting time. Rather, it (CSA) was indirectly related by influencing sprinting force and power, which were the greatest determinants of sprint time. Normally, muscle size is considered to be an important determinant for sprinting speed (Abe et al., 2001, 2000; Ikebukuro et al., 2011; Kubo et al., 2011; Kumagai et al., 2000). However, these studies relied on muscle thickness as a measure of size. Unfortunately, muscle thickness does not account for the irregularities (in thickness) across skeletal muscle (Wells et al., 2014), whereas CSA describes thickness across the entire width of a muscle. In support, our data revealed stronger relationships between unilateral sprinting force/power and CSA (Table II), especially in the irregular-structured VL muscle.

### Conclusion

Muscle architecture in the RF and VL was demonstrated to significantly contribute to unilateral, bilateral and asymmetrical sprinting force and power, as well as sprinting time on the Woodway Curve 3.0™ non-motorized treadmill. In this capacity, our data

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### Table III. Predictive ability of ipsilateral sprinting power on muscle architecture

<table>
<thead>
<tr>
<th>Dominant Leg</th>
<th>$R^2$</th>
<th>$R^2_{ADJ}$</th>
<th>SEE</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$p$-value</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Muscle Thickness (cm)</td>
<td>0.54</td>
<td>0.52</td>
<td>0.24</td>
<td>1.30 ± 0.25</td>
<td>0.006 ± 0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Cross-Sectional Area (cm²)</td>
<td>0.60</td>
<td>0.59</td>
<td>2.59</td>
<td>-0.19 ± 2.72</td>
<td>0.069 ± 0.011</td>
<td>0.001</td>
<td>0.945</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>VL Cross-Sectional Area (cm²)</td>
<td>0.51</td>
<td>0.49</td>
<td>6.30</td>
<td>-1.96 ± 6.61</td>
<td>0.139 ± 0.027</td>
<td>0.001</td>
<td>0.769</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Echo Intensity (au)</td>
<td>0.20</td>
<td>0.17</td>
<td>10.76</td>
<td>94.11 ± 11.29</td>
<td>-0.116 ± 0.046</td>
<td>0.018</td>
<td>0.001</td>
<td>0.018</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-Dominant Leg</th>
<th>$R^2$</th>
<th>$R^2_{ADJ}$</th>
<th>SEE</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$p$-value</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Muscle Thickness (cm)</td>
<td>0.39</td>
<td>0.36</td>
<td>0.35</td>
<td>1.25 ± 0.35</td>
<td>0.006 ± 0.002</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Cross-Sectional Area (cm²)</td>
<td>0.46</td>
<td>0.43</td>
<td>3.98</td>
<td>-1.56 ± 4.07</td>
<td>0.083 ± 0.018</td>
<td>0.001</td>
<td>0.704</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>VL Cross-Sectional Area (cm²)</td>
<td>0.43</td>
<td>0.41</td>
<td>7.08</td>
<td>0.37 ± 7.24</td>
<td>0.140 ± 0.032</td>
<td>0.001</td>
<td>0.960</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>
revealed that RF architecture played a more important role for sprinting kinetics, while muscle quality in both RF and VL affected sprint time. It would be beneficial for future investigations to determine the effect of muscle activation symmetry on TM sprinting performance and sprinting kinematic differences in relation to sprinting on land.

Acknowledgements
We would like to acknowledge Dr Rob Newton and Ian Crossing for their assistance in the preparation of this manuscript.

References


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