The effects of running a 12-km race on neuromuscular performance measures and the reliability of these measures

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Abstract

There is an increasing number of individuals participating in organised running races every year. Running involves repetitive movements and cyclical activation of lower extremity muscles, with foot-strike pattern and fatigue proposed to be contributing factors to running-related injuries. A variety of measures can be used to assess neuromuscular performance and gait of runners. The aims of this thesis were to: (1) systematically review and quality appraise articles addressing the reliability of plantar pressure (PP) distribution and centre of pressure (COP) measures in static stance, 2D video-based assessments of foot-strike pattern (FSP), and plantar-flexion isometric strength-endurance (PF_{isom}) measures (Chapter One); (2) assess the test-retest reliability of these measures in a cohort of recreationally competitive runners (Chapter Two); (3) determine the intra-rater and inter-rater reliability of 2D analyses of overground running in an outdoor environment (Chapter Three); and (4) investigate the effects of running a 12-km race on these measures (Chapter Four).

As part of the systematic review in Chapter One, forty-three articles were assessed for their methodological quality, with only 21% obtaining a high quality score (≥ 75%) based on the Consensus-based Standards for the selection of health Measurement Instruments. From the reviewed studies, the most reliable measures were: PP mean pressure, % body weight, and contact area; COP sway area and path length; FSP when using a two level classification system; and PF_{isom} peak torque and peak force.

In Chapter Two, 21 recreational runners (10 males, 11 females) completed tests of PP distribution in a bilateral stance, a 30 second eyes-closed postural balance test, and a self-selected running over task 15-m with video assessment to assess test-retest reliability. Measures of PP surface area, COP path length, FSP classification, foot-strike angle, and running speed were found to be the most reliable across intra-session and inter-session testing occasions.

In Chapter Three, the intra-rater and inter-rater reliability of 2D video analyses of overground running in an outdoor environment were assessed from 155 high-speed videos (240 Hz). These 2D video analyses were reliable for quantifying FSP, foot-strike angle, and running speed, although foot-strike angle errors of 2.5° were typical. The associated large CV (17.6%) is likely a reflection of the limited foot-strike angle range (42°) in our population.

In Chapter Four, 24 recreationally competitive runners (15 males, 9 males) completed PP distribution, postural balance, FSP, and PF_{isom} tests before and after a 12-km organised race. Running a 12-km race influenced several neuromuscular measures, notably postural control (92.1% and 22.7% increase for area 95 ellipse and path length, respectively) and PF_{isom} (10.8% decrease), confirming racing-induced fatigue. However, these alterations did not lead to observable changes in FSP, indicating that this measure might not be appropriate for quantifying fatigue in recreationally competitive runners.

Results from the systematic review highlight the need for higher quality methodological reliability studies to be undertaken to make stronger inferences about the reliability of measures of PP, COP, FSP and PF_{isom}. The two reliability studies demonstrated measures of PP surface area, COP path length, FSP, foot-strike angle, and running speed to be the most reliable. Furthermore, quantifiable declines in COP and PF_{isom} were observed post a 12-km race, confirming racing-induce fatigue.

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List of Abbreviations

COP – Centre of pressure

$\text{COP}_{\text{area95}}$ – Centre of pressure encompassing 95% of the centre of pressure data points

COP_{path} – Centre of pressure path length

COSMIN – Consensus-based Standards for the selection of health Measurement Instruments

CV – Coefficient of variation

ES – Effect size

FSP – Foot-strike pattern

ICC – Intraclass correlation

IQR – Interquartile range

κ – Kappa

m/s – Metres per second

N – number

NA – Not applicable

PF_{isom} – Plantar-flexion isometric strength-endurance

PP – Plantar pressure

SD – Standard deviation

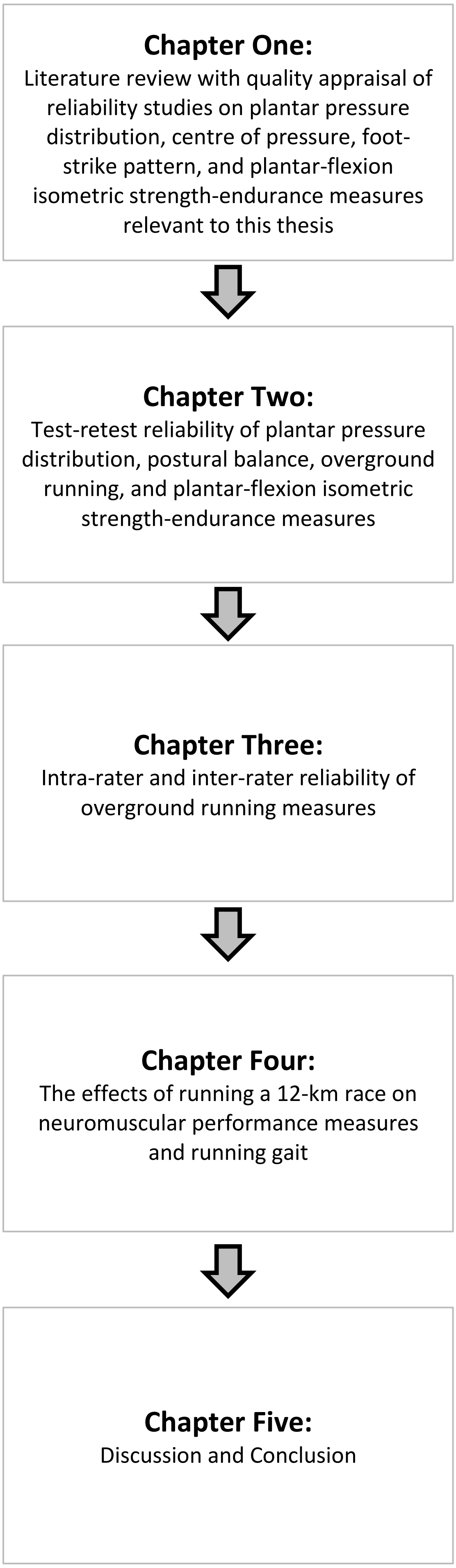
TE – Typical error

%BW – Percentage of body weight distribution

90% CI – 90% Confidence interval

Thesis Overview

The primary focus of this thesis is to determine the effects of running a 12-km race on neuromuscular performance measures and investigate the reliability of these measures. The Thesis is comprised of five chapters (**Figure 1**), with each chapter formatted as an individual article suitable for peer-review publication. Due to the nature of the format, some of the information may be repeated throughout the Thesis. Chapter One is a systematic review of the literature with quality appraisal of existing literature on the reliability of plantar pressure distribution measures in a static stance, centre of pressure measures in a static stance, classification of foot-strike patterns from 2D video-based analysis of running gait, and plantar-flexion isometric strength-endurance measures. Currently, a relatively small amount of high methodological quality articles (i.e., ≥ 75% COSMIN score) for these measures exist. Hence, a test-retest reliability study was undertaken to examine the reliability of these measures, targeting the recreationally competitive runner as participants. Two reliability studies were undertaken, and are detailed in Chapter Two and Chapter Three. Chapter Four contains a field-based study investigating the effects of running a 12-km road race on neuromuscular and running gait measures. Chapters Two and Four are presented in the same format as they were submitted to scientific peer-reviewed journals (currently under review). The final chapter (Chapter Five) summarises the findings of the systematic review and the three experimental studies included in this Thesis, and highlights practical implications, strengths, limitations, and provides suggestions for further research.



Chapter One:
Literature review with quality appraisal of reliability studies on plantar pressure distribution, centre of pressure, foot-strike pattern, and plantar-flexion isometric strength-endurance measures relevant to this thesis

Chapter Two:
Test-retest reliability of plantar pressure distribution, postural balance, overground running, and plantar-flexion isometric strength-endurance measures

Chapter Three:
Intra-rater and inter-rater reliability of overground running measures

Chapter Four:
The effects of running a 12-km race on neuromuscular performance measures and running gait

Chapter Five:
Discussion and Conclusion

Figure 1. Flow diagram of Thesis structure.

Chapter One – Literature review with quality appraisal of reliability studies on plantar pressure distribution, centre of pressure, foot-strike pattern, and plantar-flexion isometric strength-endurance measures relevant to this thesis

1. Introduction

With the increasing number of organised road races worldwide and number of finishers in events of varying lengths in the last years (http://www.arrs.net), it is unsurprising that there is an increasing amount of scientific literature available on the topic of running, spanning biomechanics[1-3], physiology[4,5], neuromuscular properties[6-8], injuries[9], fatigue[7], and performance[10]. In both clinical and research settings, various subjective and objective measures are used to assess runners, which include plantar pressure distribution[11], centre of pressure movement from postural tasks[12], video-based assessments of foot-strike and running gait[13-20], and plantar-flexion isometric strength-endurance tests[6,21,22].

In runners, a change in plantar pressure (PP) distribution and load due to fatigue or other factors (e.g., footwear) can increase the risk of certain type of foot injuries[23,24]. For instance, PP distribution under the metatarsal heads has been demonstrated to increase post-marathon[24], suggestive of an increased likelihood of metatarsal head stress fractures. In a clinical context, podiatrists and other health care professionals use plantar pressure mats to screen for any plantar pressure distribution abnormalities or alterations[25].

Centre of pressure (COP) measurements from force plates are frequently used to assess postural control in both healthy and patient populations[26]. Postural control regulates our ability to maintain an upright stance and is necessary in the performance of daily tasks[27]. Previous studies in runners have found significant differences in total, anterior-posterior, and medio-lateral COP path length measures after an ultra marathon[12], indicating deficits in postural control subsequent to running-induced fatigue.

Two-dimensional video-based assessments are a common tool to determine foot-strike pattern (FSP) in runners and assess running gait. In the scientific literature, the use of two[28] to five[29] categories for foot-strike pattern classifications are reported; but the two most common foot-strike classifications are: 1) rear-foot, mid-foot, and fore-foot[13-19,30-33]; and 2) rear and non-rear-foot[20,28,34-36]. Rear-foot patterns are typically associated with greater impact forces[37] and vertical loading rates[37,38] than fore-foot striking patterns[37,39]. These higher vertical loading rates are suggested to predispose rear-foot strikers to hip and knee injuries compared to fore-foot strikers[36]. Conversely, redistribution of joint work to the ankle with fore-foot striking increases susceptibility to Achilles tendinopathies and foot pain in fore-foot strikers[36].

The plantar-flexor muscles play a critical role in terms of the support phase and forward progression of the body during locomotion[40]. Ankle fatiguing protocols have been shown to decrease ankle angle at initial contact during running[22], with a 5-km run shown to decrease the maximum voluntary isometric contraction torque of the plantar-flexors by 27%[6]. In clinical settings, hand held dynamometers[41,42] or repetitive heel raises[43-46] are commonly used to measure the strength and endurance of the plantar-flexor muscles.

Given that plantar pressure, static balance, 2D video analyses, and force plates for strength-endurance are common tools used in the assessment of runners, it is important to understand their reliability. Knowledge on the reliability of measures is important before interpreting changes in measures. Currently, a combined systematic review for PP distribution, COP, video-based assessment of FSP, and plantar-flexion isometric strength-endurance with appraisal of their methodological quality is currently not available.

Therefore, the aim of this systematic review of the literature was to critically appraise and summarise research investigating the reliability of PP distribution in static stance on plantar pressure mats, COP measures in static stance from force plates, video-based assessment of FSP during running from 2D video analyses, and plantar-flexion isometric strength-endurance (PF_{isom}) measures from healthy participants.

2. Methods

2.1 Systematic search

The systematic reviews conducted as part of this work adheres to the structures and reporting requirements of the PRISMA statement. The SCOPUS®, SportDISCUS™, and PubMed databases were systematically searched on the 6th of September, 2017. Four independent searches were conducted to address the reliability of: PP, COP, FSP, and PF_{isom} measures.

The following search syntaxes were used for the four independent systematic searches:

1. Reliability of PP distribution in static stance: **reliability AND "plantar pressure".**
2. Reliability of COP in static balance: **reliability AND balance AND "force plate".**
3. Video-based assessment of foot-strike pattern during running: **reliability AND (footstrike OR “foot strike”) AND video.**
4. Plantar-flexion isometric strength-endurance measures: **(plantarflexion OR "plantar flexion" OR "triceps surae") AND reliability AND isometric.**

To be included, articles needed to:

1. Address test-retest (intra-session or inter-session) or rater (intra-rater or inter-rater) reliability;
2. Derive reliability metrics from a cohort of “healthy” individuals;
3. Include participants 18 years or over;
4. Use Pearson correlation, coefficient of variation, kappa, and/or intra class coefficient statistical measures;
5. Be an original research article published in a peer-reviewed journal;
6. Be available in the English language.

Articles that solely reported on the reliability of measures in a patient population (i.e., individuals with pathologies or injuries) were excluded. Reliability data reported in symposium reports or conference abstracts were not considered.

For the four independent searches, articles were excluded if:

1. Reliability of PP distribution in static stance was not addressed (i.e., only dynamic conditions assessed) or when in-sole plantar pressure sensors were used.
2. Reliability of COP under a static balance condition was not reported (i.e., only dynamic conditions were assessed) or when force plates were not used.
3. Reliability of foot-strike pattern during running was not assessed using 2D video cameras.
4. Reliability of plantar-flexion strength-endurance measures were not isometric (e.g., isokinetic or isotonic conditions) or when dynamometers were used.

One reviewer conducted the database search (LM) and compiled all articles in a reference manager software (Endnote™, version X8, Clarivate Analytics, Philadelphia, PA, USA). Duplicate articles from the database search were removed before screening the titles, abstracts, and full-text articles in that order for inclusion and exclusion. Results from the screening process were verified independently by a second reviewer (KHL). The process was repeated for the reference list of all articles meeting the inclusion criteria until no additional articles of relevance could be found.

Due to the limited number of articles addressing reliability of plantar-flexion isometric strength-endurance measures when the use of dynamometers was an exclusion criteria (*n* = 1); the systematic search regarding PF_{isom} was repeated and articles using dynamometers were included. The search strategy and article selection processes used for the four independent searches are illustrated in **Figures 2 – 5**.

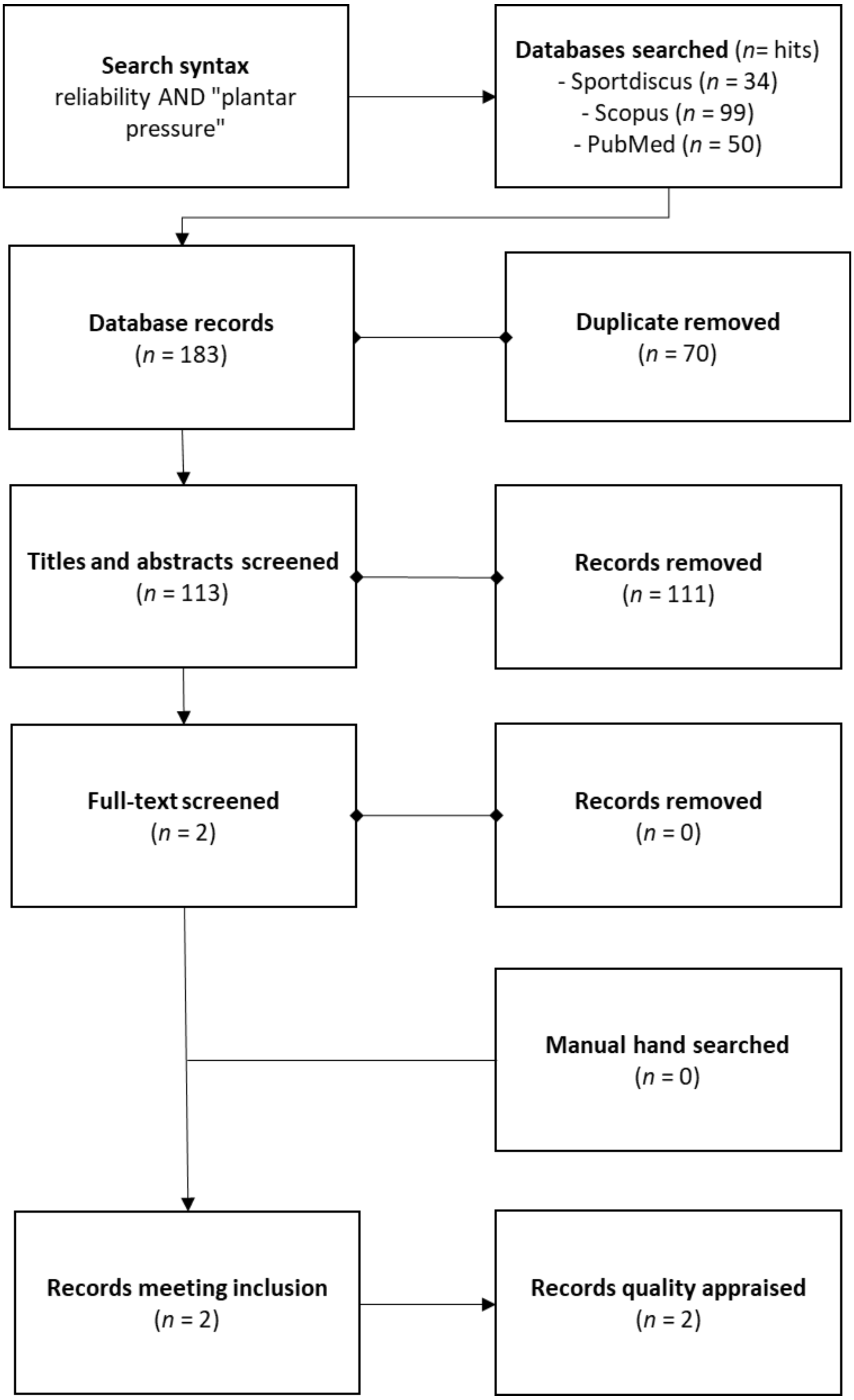


Figure 2. Flow chart of the article selection process of studies addressing the reliability of plantar pressure distribution in static stance from plantar pressure mats.

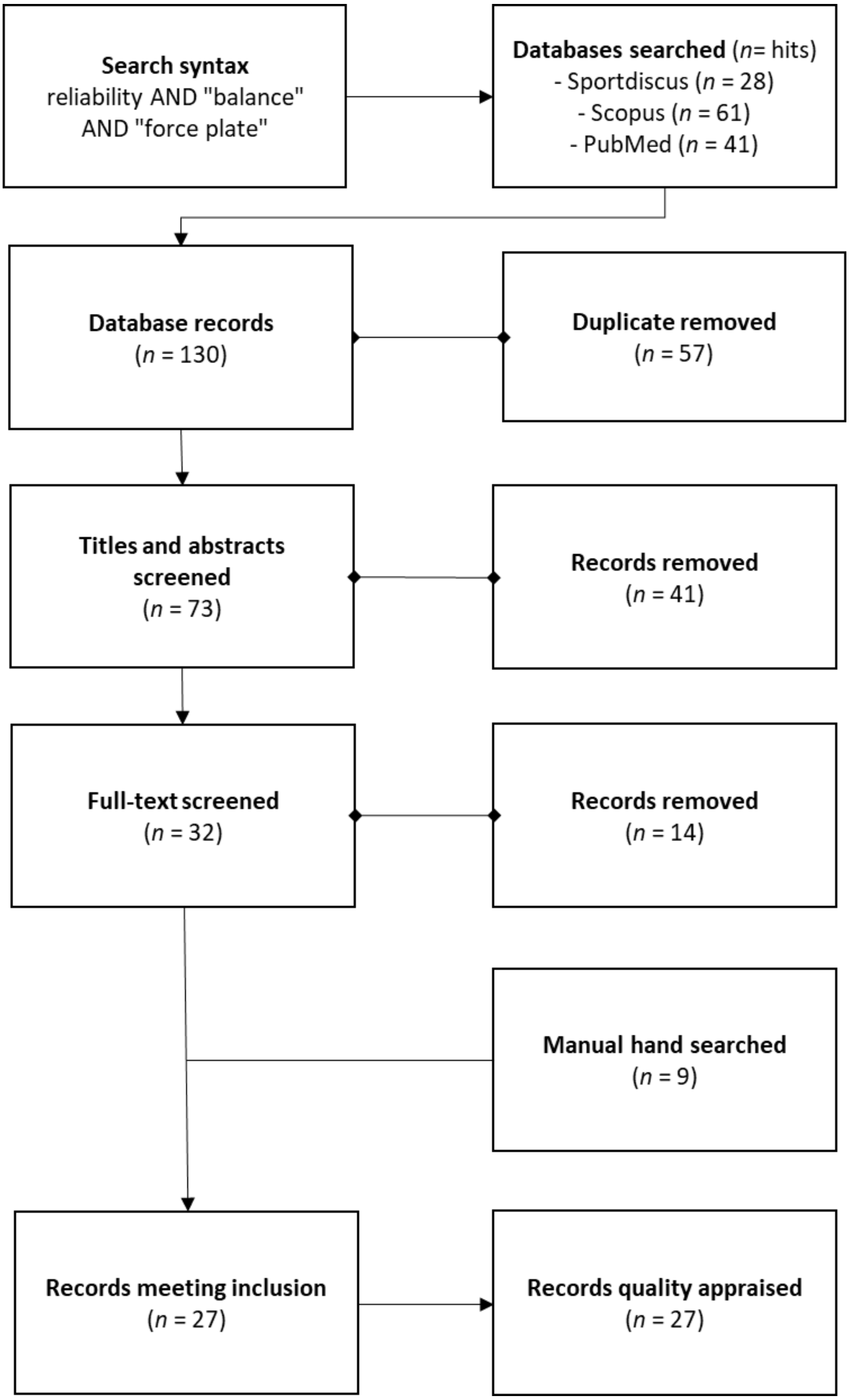


Figure 3. Flow chart of the article selection process of studies addressing the reliability of force plate COP measures from static balance tasks.

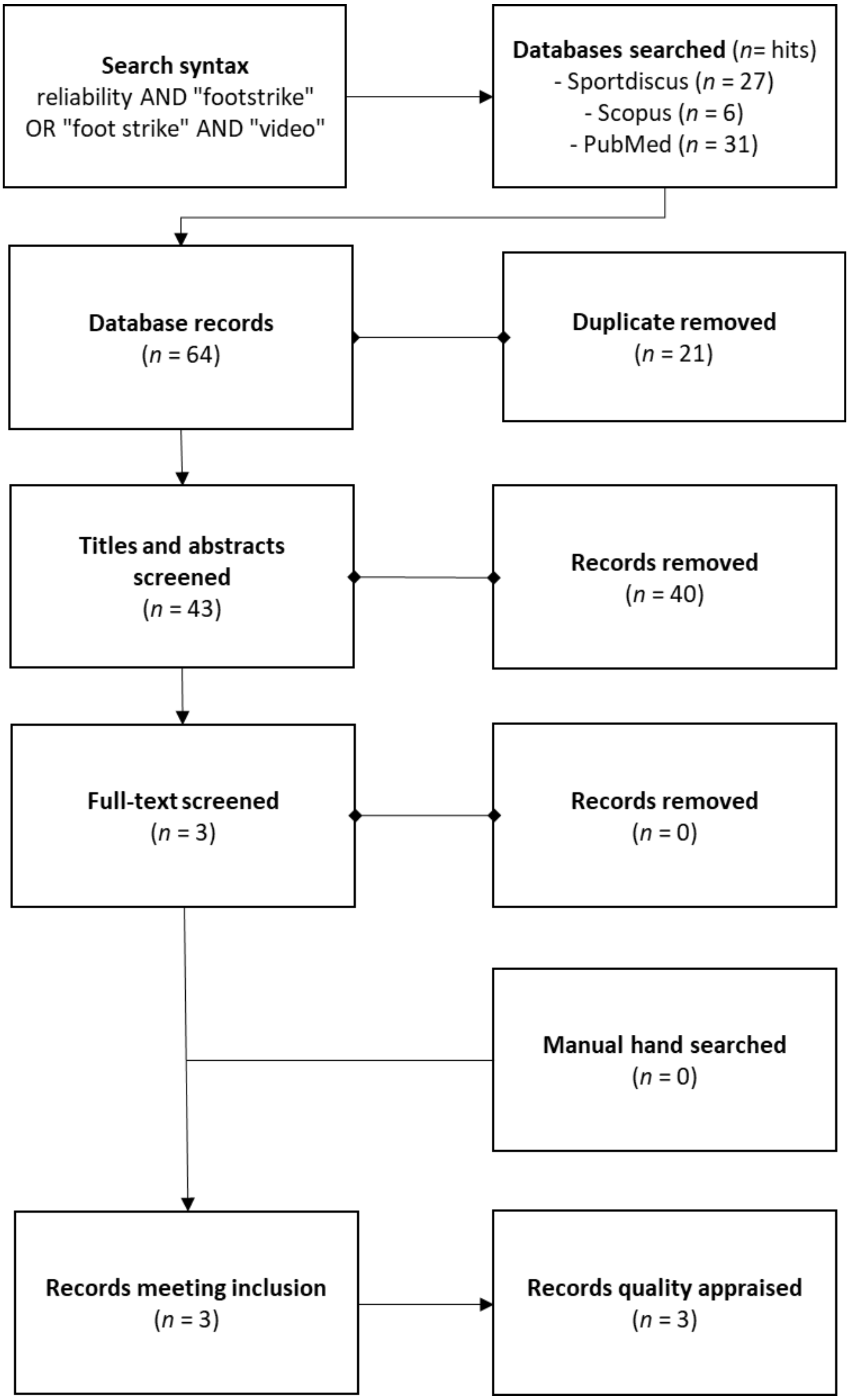


Figure 4. Flow chart of the article selection process of reliability studies addressing 2D video assessment of foot-strike pattern classification during running.

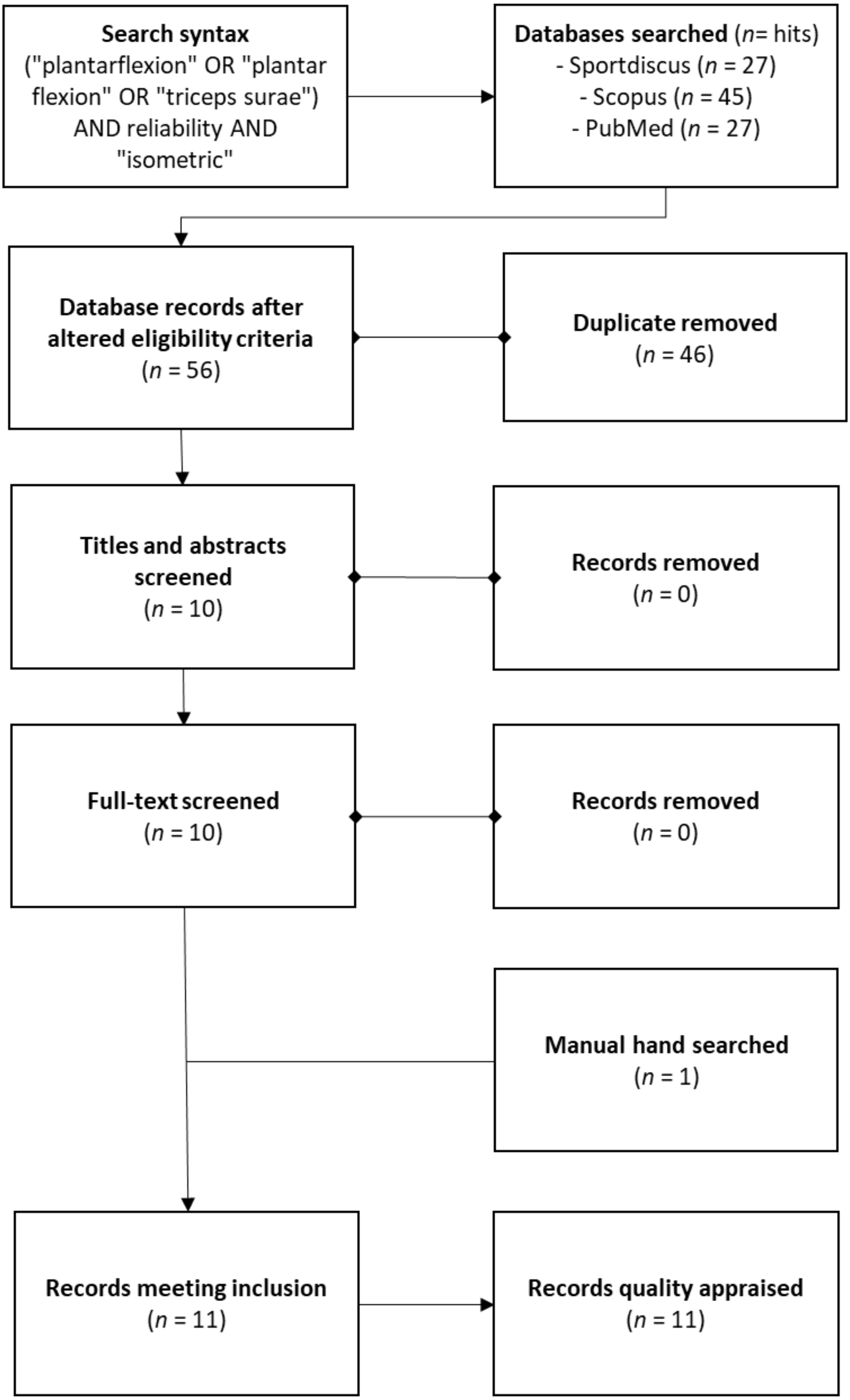
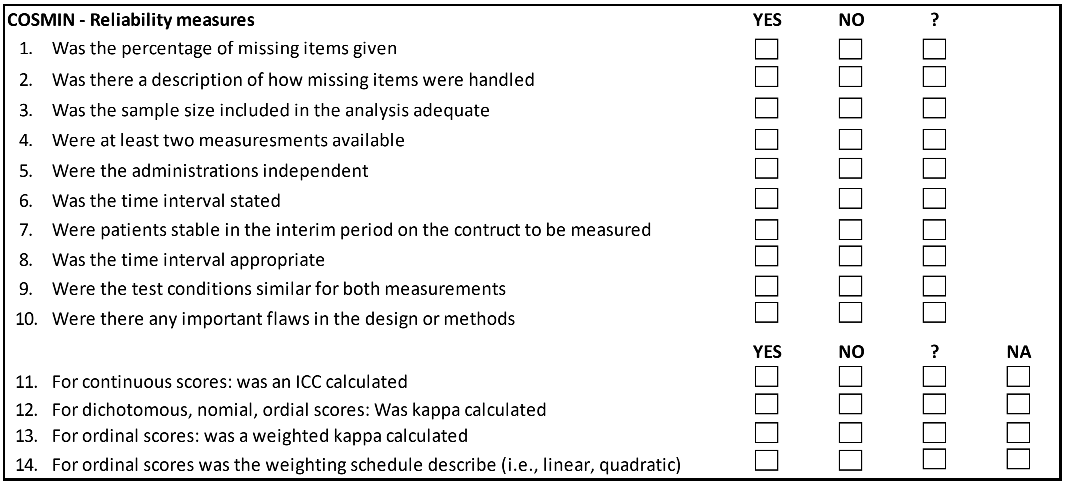


Figure 5. Flow chart of the article selection process of studies addressing the reliability of plantar-flexion isometric strength-endurance measures.

2.2 Quality assessment

The Consensus-based Standards for the selection of health Measurement Instruments (COSMIN) checklist was used to determine the quality of the articles identified in the four independent systematic searches. The 14-item COSMIN reliability checklist was chosen given that it could be used to assess test-retest, inter-rater, and intra-rater reliability studies[47], and has demonstrated high inter-rater agreement (percentage agreement: 94%; intraclass kappa: 0.77)[48]. Each COSMIN item was scored as 'Yes', 'No' or '?' according to the COSMIN manual. An item was scored '?' if there was insufficient information provided by the article to respond to the assessed criteria. Items 11 – 14 could also be scored as 'NA' (not applicable). A template of the COSMIN score sheet used to quality appraise the articles retrieved is provided in **Figure 6**.



COSMIN - Reliability measures	**YES**	**NO**	**?**	
1. Was the percentage of missing items given	☐	☐	☐	
2. Was there a description of how missing items were handled	☐	☐	☐	
3. Was the sample size included in the analysis adequate	☐	☐	☐	
4. Were at least two measuresments available	☐	☐	☐	
5. Were the administrations independent	☐	☐	☐	
6. Was the time interval stated	☐	☐	☐	
7. Were patients stable in the interim period on the contruct to be measured	☐	☐	☐	
8. Was the time interval appropriate	☐	☐	☐	
9. Were the test conditions similar for both measurements	☐	☐	☐	
10. Were there any important flaws in the design or methods	☐	☐	☐	
	YES	**NO**	**?**	**NA**
11. For continuous scores: was an ICC calculated	☐	☐	☐	☐
12. For dichotomous, nomial, ordial scores: Was kappa calculated	☐	☐	☐	☐
13. For ordinal scores: was a weighted kappa calculated	☐	☐	☐	☐
14. For ordinal scores was the weighting schedule describe (i.e., linear, quadratic)	☐	☐	☐	☐

Figure 6. Modified COSMIN scoring sheet for reliability studies, with the option of '?' added to items 1, 2, 4, 6, 10-12, and 14.

Two reviewers (LM and KHL) met before independently quality assessing the articles to agree on how to score each item. The reviewers agreed to score Item 1 'Yes' if the article explicitly stated that all participants' data were included in the analyses or how missing items were handled; and Item 3 was scored 'Yes' if the sample size was 30 or over.

Both reviewers then conducted individual assessments of the methodological quality of all articles subsequently meeting inclusion criteria ($n = 43$). After independent assessments by the two reviewers, any inconsistencies in scoring were discussed until a consensus was achieved on the remaining items, in accordance to recommendations for using the COSMIN checklist[48]. A third reviewer was identified to reconcile differences in opinion, but was not needed. Final quality assessment scores were expressed as a percentage of applicable items, with higher percentages indicating articles of higher methodological quality. Items that were scored 'Yes' received a point. Due to the nature of Item 10 ("Were there any important flaws in the design or methods of the study?"), a score of 'No' received a point. A final percentage score was derived for each article as:

$$\textit{Quality score (\%)} = \frac{number\ of\ points\ scored}{number\ of\ eligible\ points} \times 100\ \%$$

A final quality assessment score of 75% or higher was deemed to reflect a reliability study of high methodological quality[49].

2.3 Data extraction

Information concerning study aims, design, population, equipment, testing protocol, outcome measures, statistical analysis, and results were extracted from each article using a standardised format by one reviewer (LM). To ensure completeness of extraction, the data were verified by a second reviewer (KHL). Study design was classified as test-retest (i.e., intra-session or inter-session) or rater (intra-rater or inter-rater) reliability studies.

2.4 Data analysis

Data were managed and analysed using Microsoft Excel 2016 (Microsoft Corporation, Redmont, WA, USA). Descriptive statistics for the data were expressed using means and standard deviations (mean ± SD), median and inter-quartile ranges (median [lower quartile, upper quartile]), mode, ranges (minimum to maximum), counts (n), or percentages (%) depending on the data type. When possible, weighted means based on sample size were calculated for age, height, and weight of cohorts. Meta-analysis was not attempted due to the heterogeneity of outcome measures and reliability statistics used across studies. The agreement of categorical ratings based on kappa (κ) were interpreted as: poor ($\kappa < 0.40$), fair ($0.40 \geq \kappa < 0.60$), good ($0.60 \geq \kappa < 0.80$), and excellent ($\kappa \geq 0.80$)[50,51]. Relative reliability of measures based on intraclass correlation (ICC) measures were considered as: poor (ICC < 0.40), fair (0.40 ≥ ICC < 0.75), good (0.75 ≥ ICC < 0.90), and excellent (ICC ≥ 0.90)[52]. Absolute reliability was deemed acceptable when the CV was < 10%, as is common practice in sport and exercise science[53], and suboptimal when ≥ 10%.

3. Results

3.1 Literature search and quality appraisal

A total of two articles for plantar pressure distribution (**Figure 2**), 27 articles were reviewed for COP (**Figure 3**), three articles for foot-strike pattern (**Figure 4**), and 11 articles for plantar-flexion isometric strength-endurance (**Figure 5**). Quality assessment scores ranged from 9.1 – 90.9% and are presented in **Table 1** for each article.

Table 1. COSMIN quality appraisal scores for each of the assessed articles.

Article	Missing items %	Missing items	Sample size	At least two measurements	Independent administrators	Time interval	Patients stable	Time interval	Test conditions	Important flaws	ICC	Kappa	Weighted kappa	Weighting schedule	Score (%)
PP															
Izquierdo-Renau et al.[80]	N	N	Y	Y	Y	?	?	Y	Y	Y	Y	NA	NA	NA	54.5
Vallejo et al.[27]	N	N	Y	Y	?	Y	?	?	Y	Y	Y	NA	NA	NA	45.5
COP															
Bauer et al.[56]	Y	Y	Y	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	81.8
Bauer et al.[57]	Y	Y	Y	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	81.8
Carpenter et al.[58]	?	?	Y	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	63.6
Chang et al.[62]	N	N	Y	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	63.6
Chiari et al.[64]	N	N	N	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	54.5
Clark et al.[59]	Y	Y	Y	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	81.8
Corriveau et al.[55]	Y	Y	Y	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	81.8
Corriveau et al.[54]	Y	Y	N	Y	?	Y	Y	Y	Y	Y	NA	NA	NA	NA	72.7
Doyle et al.[65]	N	N	Y	Y	?	N	Y	?	Y	Y	Y	NA	NA	NA	63.6
Geurts et al.[66]	Y	Y	N	Y	?	Y	?	Y	Y	Y	N	NA	NA	NA	54.5
Golriz et al.[24]	Y	Y	Y	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	81.8
Hill et al.[60]	N	N	N	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	45.5
Kitabayashi et al.[67]	Y	Y	Y	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	81.8
Lafond et al.[99]	N	N	N	Y	?	Y	Y	Y	Y	N	Y	NA	NA	NA	63.6
Letz et al.[70]	Y	Y	Y	Y	?	Y	?	Y	Y	Y	N	NA	NA	NA	63.6
Levy et al.[71]	Y	Y	Y	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	72.7
Lin et al.[72]	N	N	Y	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	63.6

Mani et al.[91]	N	N	Y	Y	?	Y	Y	?	Y	N	Y	NA	NA	NA	63.6
Mattacola et al.[61]	N	N	N	Y	?	Y	Y	Y	Y	Y	Y	NA	NA	NA	54.5
Moghadam et al.[63]	N	N	N	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	54.5
Pinsault et al.[73]	N	N	N	Y	?	Y	Y	Y	Y	N	Y	NA	NA	NA	63.6
Raymakers et al.[74]	Y	Y	Y	Y	?	Y	?	Y	Y	Y	N	NA	NA	NA	63.6
Riley et al.[75]	N	N	N	Y	?	N	?	?	?	Y	N	NA	NA	NA	9.1
Santos et al.[76]	N	N	N	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	54.5
Schmid et al.[77]	?	?	N	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	45.5
Swanenburg et al.[100]	N	N	Y	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	81.8
Takala et al.[79]	N	N	N	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	45.4
FSP															
Damsted et al.[29]	N	N	Y	Y	Y	N	?	?	Y	Y	N	Y	Y	Y	50.0
Pipkin et al.[51]	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	NA	Y	Y	84.6
Santuz et al.[81]	N	N	Y	Y	?	N	Y	?	Y	Y	NA	N	N	N	30.8
PF$_{isom}$															
Bemben et al.[82]	?	?	Y	Y	?	Y	?	Y	N	Y	N	NA	NA	NA	36.4
Clark et al.[83]	?	?	N	Y	?	Y	Y	Y	Y	N	Y	NA	NA	NA	63.6
Clarke et al.[41]	Y	Y	Y	Y	Y	Y	?	Y	Y	N	Y	NA	NA	NA	90.9
Ford-Smith et al.[84]	N	N	N	Y	?	Y	?	Y	Y	N	Y	NA	NA	NA	72.7
Foure et al.[85]	N	N	N	Y	?	Y	?	Y	?	Y	Y	NA	NA	NA	36.4
Joseph et al.[86]	N	N	N	Y	N	Y	?	Y	?	N	Y	NA	NA	NA	36.4
Mattes et al.[101]	Y	Y	N	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	63.6
Moraux et al.[87]	Y	N	Y	Y	?	Y	?	N	Y	Y	Y	NA	NA	NA	63.6
Sleivert et al.[89]	N	N	N	Y	?	Y	Y	Y	Y	N	Y	NA	NA	NA	54.5
Spink et al.[42]	N	N	Y	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	54.5
Topp et al.[90]	Y	Y	N	Y	?	Y	?	Y	Y	Y	Y	NA	NA	NA	63.6

3.2 Plantar pressure

A summary of characteristics of the two reliability studies[25,54] that met the inclusion criteria for PP are presented in **Appendix 3**. The average quality score of these two studies was 50 ± 6.4% (45.5 and 54.5%). Neither study was deemed to be of high quality (**Table 1**). A total of 96 healthy participants were included. Weighted mean values of participant characteristics for the two studies were 39.8 ± 9.4 y, 167.4 ± 0.5 cm, and 70.2 ± 1.7 kg.

Several measures were investigated within the two assessed studies, including relative pressure-load bilaterally and unilaterally (%), and mean and peak values for plantar pressure and contact area. Both studies had a test-retest design, with time between testing sessions ranging from three to twenty days. Static plantar pressure distribution was assessed using 5 trials of 30 s in duration in one study[25], whilst the other did not state the length of the static trials[54].

Overall, inter-session reliability was greater than intra-session reliability, with good to excellent reliability reported for % (ICC: 0.95 to 0.97), mean pressure (ICC: 0.93 to 0.98), contact area (ICC: 0.93 to 0.97), and peak pressure (ICC: 0.86). Across both studies[25,54], intra-session reliability was slightly higher in the second than first testing session for all aforementioned outcome measures (ICC range: 0.92 to 0.99 versus 0.87 to 0.98), except for peak pressure where reliability was similar (ICC: 0.93 versus 0.92)[54].

3.3 Centre of pressure

A summary of characteristics of the twenty-seven reliability studies[27,55-80] that met the inclusion criteria for COP are presented in **Appendix 3**. The average quality score of the twenty-seven studies was 63.3 ± 16.2% (range 9.1 – 81.8%, **Table 1**). Seven of the studies[27,56-58,60,68,79] achieved a quality appraisal score of 75% or higher. A total of 929 healthy participants were included across these 27 studies (average sample size of 34 ± 41, range 7 – 220). Weighted mean values of participant characteristics for the appraised studies were 42.7 ± 23.9 y, 168.5 ± 6.7 cm, and 66.3 ± 7.6 kg.

The studies assessed the reliability of various COP related measures, with the most common being 'sway area', 'velocity', and 'total path length'. Most of the articles were test-retest in design, with time between trials ranging from 2 minutes to 9 months. Of the 27 articles assessed, three articles[56,63,79] investigated both test-retest and rater reliability. Most often, studies examined four different balance tasks and three trials per task, with trials typically lasting 30 s.

Reliability was poor[27,59,61,62,66,69,80] to excellent[27,55-57,68,72,73] for the various measures reported, with ICCs and CVs ranging from 0.06 to 0.97 and 17% to 28%, respectively. The lowest reliability was seen for sway area[62] and the highest for path length[68] in an eyes-open condition.

3.4 Foot-strike pattern

A summary of characteristics of the three reliability studies[29,51,81] that were quality appraised in relation to FSP are presented in **Appendix 3.** The average quality score for these articles was 55.1 ± 27.3% (range 30.8 – 84.6, **Table 1**). Only one[51] of the three studies achieved a quality score higher than 75%.

Combined, the three articles addressed 181 participants[29,51,81], with sample sizes ranging from 5 to 145. The running experience of the participants, when stated, were classified as either: 'inexperienced', 'recreational' or 'competitive'[81]. Weighted mean values of participant characteristics were 31.2 ± 2.7 y, 175.3 ± 0.6 cm, 69.8 ± 1.6 kg. The studies assessed the reliability of FSP classification, initial contact video frame, and frontal and sagittal plane kinematics. In addition, Santuz et al.[81] compared visual to plantar-pressure based classifications of FSP.

The number of categories used to classify foot-strike pattern differed between studies and ranged from 2 to 5. Classifications included: 'heel', 'heel-mid', 'rear-foot', 'mid-foot', 'mid-fore-foot', and 'fore-foot'. Furthermore, foot-strike classification was determined at different speeds in the three studies examined (range: 2.3 to 3.5 m/s, **Table 1**)[29,51,81] and in both barefoot[81] and shoed conditions[29,51,81].

All three studies examined inter-rater reliability (from 2 to 8 raters)[29,51,81], with intra-rater reliability assessed in two of the three studies[29,51]. Overall, intra-rater reliability for foot-strike pattern classification was good (κ range: 0.83 – 0.88), and fair to excellent for inter-rater reliability (κ range: 0.41 – 0.96). The lowest agreement was observed when a five FSP classification was used (κ = 0.41)[29], and the highest agreement observed with a two-level FSP classification (ICC = 0.96)[81]. No study reported percentage agreements between ratings.

3.5 Plantar-flexion isometric strength-endurance

A summary of the eleven studies[41,42,82-90] which met the PF_{isom} inclusion criteria are presented in **Appendix 3.** The average quality appraisal score for these studies was 57.9 ± 16.9% (range 36.4 – 90.9, **Table 1**). Only one study[41] achieved a quality score of 75% or higher.

Across the studies, a total of 481 'healthy' participants were examined, with an average sample size of 44 ± 43 (range: 14 - 155). Weighted mean values for participant characteristics were 43.3 ± 22.0 y, 175.7 ± 6.2 cm, and 75.7 ± 6.9 kg. All studies[41,42,82-90] measured peak torque, peak force, or rate of torque development. Furthermore, the reliability of several types of measures were also concurrently reported (e.g., electromyography and ultrasound measures). Most of the studies were test-retest in design [70,82-87,89,90], with a range of 1 h to 12 weeks between testing sessions. Three studies reported intra-rater reliability[41,42,88], with two of these studies also reporting inter-rater reliability[41,42]. Typically, protocols were 3 x 3 to 5 s maximal contractions with 30 s of rest (up to 180 s of rest) between contractions. Three studies did not state rest periods[42,86,89].

Overall, results report excellent intra-session reliability for peak torque[86,90]. Inter-session reliability was generally good to excellent for peak torque and force, good for mean force, and poor for peak rate of torque development (ICC: 0.13[89]). Where reported, CV values were generally deemed acceptable (i.e., below 10%)[42,82,83,85], although less than optimal for select age groups (25-29, 30-34, 65-69, 70-74, and 75-79[82]) . Intra-rater reliability of PF_{isom} measures was fair to excellent (ICC = 0.56 to 0.98), whilst inter-rater reliability ranged from poor to good (ICC range= 0.15 to 0.82) for peak[41] and mean force[42] .

4. Discussion

This review critically appraised and summarised research addressing the reliability of four different biomechanical measures commonly used in research and clinical settings to assess runners. From the 43 studies examined, only 21% were deemed to be of high methodological quality according to the COSMIN reliability checklist. The reliability of plantar pressure (PP) distribution measures from plantar pressure mats in static stance was good to excellent for percent body weight (%BW) distribution, mean pressure, contact area, and peak pressure. Reliability of centre of pressure (COP) measures from force plates in static stance was the most researched (*n* = 27), with the reported reliability of measures ranging from poor to excellent. Video-based assessment of foot-strike pattern (FSP) classification during running was dependent on the number of categories used to classify FSP, with higher reliability observed when using a lower number of categories. Plantar-flexion isometric strength-endurance (PF_{isom}) measures from healthy participants were generally reliable, except for rate of torque development.

4.1 Plantar pressure

There are only two studies[25,54] that assess the reliability of plantar pressure measures in a static stance, both of which obtained low quality assessment scores. Static foot measurements are often used to make inferences for dynamic plantar pressure[91-93] and to detect the onset of pathology[94] in clinical and research settings. Therefore, the lack of high-quality reliability studies on static plantar pressure distribution is of concern.

The two reliability studies included in this review indicate that mean pressure, %BW, and total and individual foot contact area are reliable between sessions[25,54], with peak pressure demonstrating lower reliability than mean pressure[54]. Hence, it could be recommended to clinicians and researchers to make inferences on changes in an individual's condition based on the values of mean pressure instead of peak pressure given its higher reliability.

The two plantar pressure reliability studies were undertaken barefoot[25,54] . However, the majority of daily and gait activities are completed wearing shoes. Research has shown differences in the way feet and shoes interact with the ground[95-97] and how individuals run barefoot compared to with shoes[98]; hence, it might be relevant to undertake plantar pressure measurements in shod conditions as well, with currently limited information on the reliability of such plantar pressure measures in adults in good general health.

4.2 Centre of pressure

Concisely summarising or making firm inferences about the reliability of COP measures proved difficult due to the heterogeneity in the age of the populations examined, equipment used, testing protocols, and outcome measures examined. Sway area, path length, and velocity of the COP during balance tasks were most commonly reported, and were associated with poor to excellent reliability levels (ICC range: 0.06 – 0.95). Although it has been proposed that other COP measures may provide a more in depth understanding of postural balance, these measures tend to be harder to comprehend and thus may be harder to integrate into clinical practice level than sway area, path length, and velocity.

Results from the highest quality appraised articles indicate that sway area[57,79] and path length[57,60,68] exhibit good to excellent reliability within and between sessions in both eyes open and eyes closed conditions. Measures relating to velocity of the COP from eyes open balance tasks also demonstrate good to excellent test-retest reliability when 2 trials or more are preformed, with 4 trials proving to be the most reliable[27]. Based on the high-quality studies[27,56-58,60,68,79], clinicians and scientists can be confident that sway area and path length measures from balance tests in both eyes closed and eyes open conditions are reliable, and may be useful to monitor changes over time in healthy populations. Velocity measures, however, should probably be derived from a minimum of 2 trials to be deemed reliable.

The other studies addressing reliability of COP measures received lower quality scores because of failure to report key methodological information (e.g., equipment or subject characteristics missing, handling of missing data not reported, or independent administration unclear). Although, these studies contribute to our understanding of the reliability of COP measures, higher quality methodological studies would be beneficial to make stronger inferences regarding reliability of COP measures in static stance.

Of the three studies[57,58,61] that assessed different foot placements, the reliability of COP measures in a narrow and a normal stance were similar in two of the studies, both in eyes open[57,58] and eyes closed conditions[57]. The majority of studies[27,56-59,61,63,66,67,69,73-75,77,79,80,99] standardised foot placement by either tracing or implementing a predetermined foot width or angle. These practices likely improve reliability of measures by promoting reproducibility of foot placement, although they may not reflect habitual foot placement of individuals.

Overall, results from the reliability studies reviewed show good to excellent reliability of COP measures from 3 x 30 s assessments. A few studies[27,55,74] did demonstrate that averaging performance across several trials produced more reliable outcomes than a single trial. Currently, it is unclear whether a balance task of longer duration than 30 s is associated with higher reliability of measures.

4.3 Foot-strike pattern

Considering the growing number of runners and research studies on running populations, there are relatively few studies investigating the reliability of FSP classification. Amongst the reliability studies quality appraised, the reliability of FSP identification was dependent on the number of FSP classifications used. Sampling rate differed across studies (range: 120 to 550 Hz), which could also influence reliability results, with higher sampling rates enabling more accurate identification of initial foot-ground contact.

Santuz et al.[81] was the only study to report the reliability of individual FSP at different speeds and in different shoe conditions. They found barefoot running (speed = 2.8 ± 0.4 m/s) was the most reliable condition for identifying rear-foot and fore-foot strikes[81], with shod running at a speed of 2.3 ± 0.3 m/s being the most reliable for mid-foot strike identification[81]. It has been demonstrated that the proportion of foot-strikes changes at speeds over 4.9 m/s[14,33,100], which could influence results of reliability studies.

All of the reliability studies meeting the inclusion criteria were conducted in a laboratory; however, most running is performed outdoors. As a result it is unlikely the reliability results from these studies would directly translate to a real-world setting. Research has demonstrated running gait is different when running on a treadmill compared to overground[101]. Moving forward, more reliability studies should be conducted in outdoor settings and a consensus on FSP classifications and video sampling rate would aid in comparing findings from different sources.

4.4 Plantar-flexion isometric strength-endurance

Overall, PF_{isom} measures demonstrated good to excellent (ICC: 0.77 to 0.99) reliability for peak force and torque. The studies involved participants being assessed whilst in a seated position with either a hand-held or isokinetic dynamometer. Although the measures of peak and mean torque were found to be reliable in these studies, plantar-flexors are functionally activated when in stance or during locomotion[40] . Therefore, assessing plantar-flexion strength in stance would be a more valid measure reflecting plantar-flexor function.

Age of the participants was reported to affect the reliability of maximal plantar-flexion force measures[82], with generally good to excellent reliability in individuals aged 20 to 64 y and poor to fair reliability in individuals aged 65 to 79 y. The lower reliability in older participants could be the result of sarcopenia, age-related muscle weakness, and lower physical activity levels with aging. Indeed, the maximal number of single-legged heel rises has been shown to decrease with age and lower physical activity levels in both males and females[102].

Rate of torque development from PF_{isom} exhibited poor reliability[89,103]. These results are consistent with findings of more functional type exercises (i.e., squat, countermovement jump, and long jump) reflecting lower-limb strength, wherein the reliability of rate of torque development was less than optimal[104] . Furthermore, research has suggested there is no association between the ability to generate isometric force and dynamic deadlift strength; however, the rate of torque development during an isometric mid-thigh pull is likely to be a better indicator of explosive ability than maximal strength[105]. Clinicians and researchers should be careful when interpreting changes in rate of torque development measures, as they are less reliable than other strength measures.

5. Conclusion

A total of 43 reliability articles were quality assessed as part of this systematic review focusing on measures of plantar pressure distribution, centre of pressure, video-assessment of foot-strike pattern, and plantar-flexion isometric strength-endurance measures. From these studies, the most reliable measures are: PP mean pressure, %BW and contact area; COP sway area and path length; FSP when using two classifications; and PF_{isom} peak torque and peak force. However, only nine of the articles reviewed (21%) were deemed to have high methodological quality. This finding alone highlights the need for higher quality methodological reliability studies to make inferences about changes in healthy cohorts, particularly for measures of PP and FSP given the relatively low number of reliability studies in these areas.

Research questions

This thesis aimed to investigate the effect of running on aspects of fatigue and neuromuscular control in a real-world environment; however, as the systematic review demonstrated there is currently a lack of quality reliability studies for measures of plantar pressure (PP) distribution, centre of pressure (COP), foot-strike pattern (FSP) and plantar-flexion isometric strength-endurance (PF_{isom}). Therefore, the research aims were:

1. To determine the intra-session, inter-session, intra-rater, and inter-rater reliability of PP, COP, FSP and PF_{isom}

2. To contribute worthwhile reliability data of PP, COP, FSP and PF_{isom} for use in clinical practice

3. To investigate the effect of a 12-km running event on measures of PP, COP, FSP and PF_{isom}

Chapter Two – Test-retest reliability of plantar pressure distribution, postural balance, overground running, and plantar-flexion isometric strength-endurance measures

1. Introduction

Pressure platforms are used to assess plantar pressure distribution in both static and dynamic conditions in both scientific and clinical contexts, with only two studies identified in the previous chapter of relatively low methodological quality found to address the reliability of measures from static trials[25,54]. Given that these measures are used to track changes over time, alterations in plantar pressure distribution, or the presence of weight distribution abnormalities, it is important to further address the reliability of static plantar pressure measurements.

Postural control regulates our ability to maintain stability in upright stance[106]. Visual, somatosensory, and proprioceptive inputs are used in optimising postural stability during activities of daily living[106,107]. Force plates are commonly used to measure postural control by tracking displacement of centre of pressure (COP) [55-58]. Measures of postural control are often used in older populations[55-58,61,69,72] as they can help estimate the risk of falling[108,109]. Results from the high methodological quality articles indicate that sway area[57,79] and path length[57,60,68] exhibit good to excellent reliability within and between sessions in both eyes open and eyes closed conditions. However, there is heterogeneity in the literature addressing centre of pressure reliability of measures due to difference in the age of cohorts, equipment used, testing protocols, outcome measures, and methodological quality. As such, it is important that reliability data are specific to testing protocols used and investigated populations.

The use of 2D videos to analyse running gait is common in sport science and in clinical settings[13,15,18]. The standardisation of running speed is important in terms of reproducibility of findings and monitoring changes in running gait. Treadmill-based analyses are typically used in clinical gait assessments and enable the standardisation and control of running speed[29,51,81]; however, treadmill running does not always reflect overground running[101]. When assessing running gait overground, runners are often required to target a selected speed[14] where a margin of error of ± 5% is deemed acceptable[110,111]. However, self-selecting running speed might provide greater insights at an individual level and be more clinically relevant. To date, there is limited information on the reliability of running gait measures in field-based settings using 2D video analyses.

Isokinetic[82,85,86] and hand-held dynamometers[41] or repetitive single-legged heel raises[44] are often used to determine isokinetic and isometric strength of the plantar-flexor muscles in healthy and patient populations[112]. Dynamometers[83,85,86,90] and repetitive single-legged heel raise performance[44,102] have proven reliability; however, both of these assessment means take time, with the isokinetic dynamometer usually assessed in a seated position. Given that the plantar-flexors are involved in bipedal postural regulation and locomotion, assessing their function in an upright stance is more functionally relevant. To date, there are no reports on the reliability of maximal isometric plantar-flexor strength assessments completed while standing.

Plantar pressure distribution, postural control, 2D video analyses, and plantar-flexion isometric strength-endurance are all functionally relevant to runners. Therefore, the aim of this study was to investigate the reliability plantar pressure (PP) distribution in static stance; COP measures in static stance; video-based assessment of foot-strike pattern (FSP), foot-strike angle, and speed during running from 2D video analyses; and plantar-flexion isometric strength-endurance measures (PF_{isom}) in recreational runners.

2. Methods

2.1 Participants

Twenty-one individuals (10 males, 11 females) volunteered to participate (**Table 2**). Inclusion criteria were 18 years or over, free from any musculoskeletal or neurological injuries, and able to run 10 km. Participants were recruited via word-of-mouth, social media platforms, and pamphlets placed in race packs of a local race event. Participants were asked to refrain from strenuous or vigorous exercise 4 hours prior to testing, as well as the ingestion of caffeine 2 hours prior to testing. All participants provided written informed consent prior to participation. The protocol was approved by the Human Research Ethics

Committee of the University of Waikato [HREC(Health)#11] and in accordance with the Declaration of Helsinki.

Table 2. Participant and shoe characteristics of test-retest participants. Values are means ± standard deviations and medians (1st quartile, 3rd quartile).

	Male (*n* = 10)	**Female (*n* = 11)**	**Total (*n* = 21)**
Participant			
Age (y)	47.9 ± 15.7	39.4 ± 13.4	44.0 ± 14.9
Height (cm)	178.8 ± 7.7	166.2 ± 5.6	172.8 ± 9.2
Mass (kg)	80.4 ± 9.8	63.2 ± 7.8	72.2 ± 12.4
Running experience (y)	5 (3.5, 25)	4 (3, 20)	5 (3, 20)
Runs (per week)	6 (4, 7)	3 (1, 5)	5 (3, 6)
Shoe			
Mass (g)	285.7 ± 36.6	234.9 ± 23.9	261.6 ± 40.0
Heel height (mm)	20.6 ± 9.7	25.4 ± 4.2	23.5 ± 6.9
Heel-to-toe drop (mm)	11.1 ± 6.6	8.4 ± 3.2	9.8 ± 5.3

All participants were required to attend one session that included repeated measures at the University of Waikato Adams Centre for High Performance Sports Laboratory. Upon arrival at the laboratory, participants completed a baseline questionnaire that included general characteristics, self-reported foot-strike pattern, shoe characteristics, and running participation. Participants were familiarised with the testing procedures and each apparatus was zeroed before every trial. Plantar pressure distribution, postural balance, running gait, and plantar-flexion isometric strength-endurance were tested sequentially, with participants wearing their own running shoes throughout the testing session.

Each participant completed 3 x 3 trials for each test, with the exception of PF_{isom}. Given the maximal nature of the PF_{isom} test, only one set of 3 trials was completed at the end of the session following the completion the three other tests (**Figure 7**). Hence, participants completed a total of 9 trials each for plantar pressure distribution, postural balance, and video-based running gait assessment, and 3 trials for PF_{isom}. This design allowed for intra-session and inter-session reliability measures for be calculated for all tests, with the exception of PF_{isom} where only intra-session metrics could be examined.

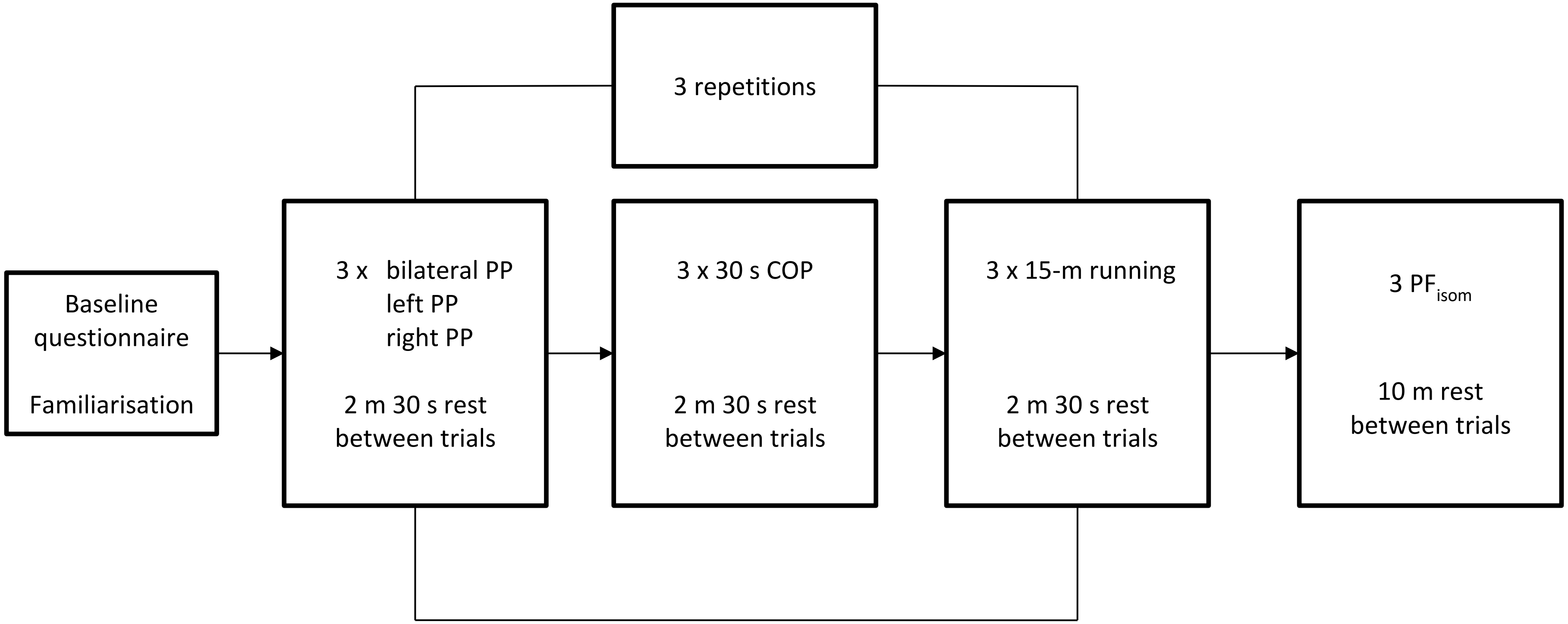


Figure 7. Test-retest reliability testing procedure.

2.2 Plantar pressure distribution

Plantar pressure was collected using the FootWork pressure plate (40 Hz sampling frequency) and Footwork Pro software (Amcube, UK). Participants stood on the platform and were instructed to walk in place for a few seconds before stopping in a self-selected comfortable stance position[25,54] and to remain as still as possible, looking straight ahead with arms by their sides. Once in a static stable position, 1-s of plantar pressure distribution data were recorded as per the manufacturer's recommendations. Participants were then instructed to move their left foot to the middle of the pressure plate and place their right foot next to the pressure plate on a surface level with the plate. Participants simulated walking again before stopping in a self-selected comfortable stance, looking straight ahead with their arms at their sides. The participant completed the same test on the right hand side. Participants completed this sequence of testing a total of three times, with 2 min 30 s rest between trials. The software was subsequently used to extract the relative pressure-load (%) distributed in anterior, posterior, right, and left areas.

2.3 Postural balance

Postural balance was assessed by using an AMTI AccuGait Optimized force plate sampling at 150Hz and Balance Clinic software version 2.03.00 (Advanced Mechanical Technology Incorporated, Watertown, MA, USA). Participants were instructed to stand on the force plate with their feet together (toes and heels touching), arms by their side, and to close their eyes whilst attempting to remain as still as possible. Once the participant had been in the testing position for 3 s, 30 s of data were recorded. No verbal encouragement or feedback was given during the balance trial. Participants completed the balance test a total of three times, with 2 min 30 s rest between trials. The Balance Clinic Software was subsequently used to extract the centre of pressure path length (COP_{path}, cm) and the area of the 95th percentile ellipse (COP_{area95}, cm^2), which encompassed 95% of the centre of pressure data points, for the duration of the 30 s trial.

2.4 Video-based assessment of running gait

To assess foot-strike pattern, a 15-m runway was delineated using cones on a level rubberised indoor surface. A digital camera (Cyber-shot DSC-RX10 II, Sony, Tokyo, Japan) sampling at 240 Hz was mounted on a 62-cm high tripod in the sagittal plane, 5.5 m away from the running area to the right-hand side of participants. Participants were asked to run at their perceived 10-km race pace through the 15-m area three times, walking back to the start of the running area and given 2 min 30 s rest between trials. Siliconcoach Pro version 8 software (The Tarn Group, Dunedin, NZ) was used to assess the foot-strike pattern and foot-strike angle. Foot-strike pattern was classified as either rear-foot (first contact with the heel or rear third of the sole only), mid-foot (first contact was the mid-foot or entire foot) or fore-foot (first contact was fore-foot or front half of the shoe) as described by Hasegawa et al.[13] due to the commonality of these categories in literature[15,19,39]. Foot-strike angles were also measured as the line joining the sole of the shoe from the point of first contact and the horizontal plane of the running surface, wherein a positive angle represented a more pronounced rear-foot strike, and negative angles represented a more pronounced fore-foot strike (**Figure 8**). The foot-strike angle and foot-strike pattern were extracted from all nine trials by a single examiner (LM) with more than 2 years of practical experience in strength and conditioning and assessment of movement from 2D videos.

Figure 8. Foot-strike angle examples for rear-foot, mid-foot, and fore-foot.

2.5 Speed

Running speed of participants were measured two ways. First, running speed was extracted using the Siliconcoach Pro software from the same videos used to measure foot-strike angle and pattern. Speed was derived from the time taken to cover the middle 5-m portion of the running area. A Brower timing light system (Brower Timing System, Colorado, USA) was also used to measure speed. The timing lights were set-up at the start and end of the middle 5-m portion of the running area and 5-m running times were manually recorded.

2.6 Plantar-flexion isometric strength-endurance

To assess plantar-flexion isometric maximal strength-endurance, participants stood on two dual-axis PASCO force plates (PASCO, Roseville, CA) sampling at 500 Hz positioned under a squat rack. Participants stood under a 20 kg Olympic barbell and were instructed to “push as hard as possible” upwards against the barbell for 10 s using their calf muscles to exert force into the ground, keeping their knees straight. The height of the barbell was standardised to allow the bar to rest on participants’ shoulders while allowing slight heel lift from the ground during the exertional task. Participants warmed-up for the maximal trial by completing a trial at 50% and then at 70% maximal efforts. When participants felt ready, the maximal trial was completed. The PASCO Capstone Software version 1.4 was used to extract peak force normalised to body weight (%BW).

Strong verbal encouragements were provided throughout the trial to promote maximal force output. Given the nature of the task, a 10-minute rest between trials was allocated. To ensure adequate recovery, participants were asked to rate their recovery on the Perceived Recovery Status Scale, where 0 indicates very poorly recovered and 10, very well recovered[113] . Participants were given additional rest if their self-reported recovery was below 7 on the 11-point scale.

Unfortunately, due to technical issues with the data collection equipment, the data for the plantar-flexion isometric strength-endurance test were not saved. Therefore, no statistical analyses on the reliability of this test could be performed.

2.7 Statistical analysis

Mean and standard deviation (SD) values were computed for all variables to describe the data, whereas counts were used to describe foot-strike pattern data. Data were analysed using a customisable spreadsheet analysing consecutive pairwise trials[114]. Intra-session reliability was assessed by comparing consecutive trials within each session (i.e., 3 x Trial 1 versus Trial 2 versus Trial 3), as well as consecutive trials within the entire testing session (i.e., Trial 1 to Trial 9). Inter-session reliability was assessed by comparing individual trials across sessions (i.e., Trial 1 across sessions, Trial 2 across sessions, and Trial 3 across sessions), as well as the average of the three trials across sessions (i.e., average of Trial 1, Trial 2, and Trial 3 across sessions).

Intraclass correlation coefficients (ICC), typical error (TE), and coefficient of variation (CV) with 90% confidence intervals [lower, upper] were calculated to quantify the relative (ICC) and absolute (TE and CV) reliability measures. For the purpose of interpreting the ICC, the relative reliability of measures was considered as: poor ($ICC < 0.40$), fair ($0.40 \geq ICC < 0.75$), good ($0.75 \geq ICC < 0.90$), and excellent ($ICC \geq 0.90$)[52] . A $CV < 10\%$ was deemed to reflect acceptable absolute reliability as in common practice in sport and exercise science[53] and CV of $\geq 10\%$ was deemed suboptimal. Log-transformed values were used for interpreting all statistical ICC and CV values, except for relative pressure-load (%) and foot-strike angle where values could not be log-transformed.

Given that foot-strike pattern was a categorical variable with three levels (rear-foot, mid-foot, and fore-foot), agreement in classification scores and linear weighted kappa (κ) with 90% confidence intervals were computed to quantify reliability. The agreement of category ratings were interpreted as: poor ($\kappa < 0.40$), fair ($0.40 \geq \kappa < 0.60$), good ($0.60 \geq \kappa < 0.80$), and excellent ($\kappa \geq 0.80$)[50,51].

Finally, a customisable spreadsheet analysing validity by linear regression was used to determine the validity of running speed measures derived from Siliconcoach (practical measure) against the Brower timing lights (criterion measure[114]). Log-transformed values were used when interpreting Pearson correlation and CV values

3. Results

Descriptive and reliability statistics for intra-session and inter-session measures are presented in **Tables 3-6**. Reliability for both intra-session (ICC: 0.60 to 0.99) and inter-session (ICC: 0.55 to 0.99) were fair to excellent, with the most reliable measures being the left and right foot surface area measures in a bilateral and single foot stance, foot-strike angle, and speed. Absolute reliability was termed optimal or suboptimal for the various measures investigated, with CV values ranging from 2.57 to 44.45%. Inter-session reliability across all measures increased when averaging the three trials (**Table 6**). Foot-strike pattern agreement was excellent for both intra-session and inter-session (**Figure 9**).

Deriving running speed from Siliconcoach exhibited excellent concurrent validity against the Brower Timing Lights (r = 0.98 [0.97, 0.98], CV = 2.7% [2.5, 2.9]. The mean difference between the Siliconcoach and Brower Timing Lights was 0.3 ± 0.1 m/s, with a TE of 0.07 m/s [0.07, 0.08].

Table 3. Intra-session means, changes in mean and TE (typical error). Values are mean ± standard deviations.

	Intra-session					
	3 trials^{+}			**9 trials***		
	Mean ± SD	Change in mean	TE [90% CI]	Mean ± SD	Change in mean	TE [90% CI]
Plantar pressure						
Bilateral						
Left foot (%)	49.0 ± 7.6	0.03 ± 6.5	4.6 [4.2, 5.3]	49.0 ± 7.7	0.02 ± 7.0	4.8 [4.3, 5.6]
Right foot (%)	51.0. ± 7.6	-0.04 ± 6.6	4.6 [4.2, 5.3]	51.0 ± 7.7	-0.1 ± 7.0	4.9 [4.3, 5.6]
Left foot mean pressure (kPa)	28.0 ± 11.7	-0.2 ± 6.0	4.3 [3.8, 4.9]	28.0 ± 11.9	-0.2 ± 6.3	4.6 [4.1, 5.3]
Right foot mean pressure (kPa)	23.9 ± 7.7	-0.4 ± 4.5	3.2 [2.9, 3.6]	23.9 ± 7.8	-0.3 ± 4.4	2.6 [2.3, 3.0]
Left foot surface (cm^2)	35.2 ± 11.4	0.02 ± 3.8	2.7 [2.4, 3.1]	35.2 ± 11.6	-0.2 ± 3.7	2.8 [2.5, 3.3]
Right foot surface (cm^2)	41.2 ± 12.1	0.3 ± 4.4	3.1 [2.8, 3.5]	41.2 ± 12.3	0.02 ± 4.1	3.0 [2.7, 3.5]
Individual						
Left foot mean pressure (kPa)	25.8 ± 8.1	-0.2 ± 5.2	3.6 [3.3, 4.2]	25.8 ± 8.2	-0.2 ± 5.0	3.4 [3.0, 3.9]
Right foot mean pressure (kPa)	28.9 ± 8.8	0.4 ± 6.7	4.7 [4.2, 5.4]	28.9 ± 9.0	0.1 ± 7.0	5.0 [4.4, 5.8]
Left foot surface area (cm^2)	42.0 ± 13.4	0.1 ± 4.1	2.9 [2.6, 3.3]	42.0 ± 13.6	-0.1 ± 4.0	3.0 [2.6, 3.4]
Right foot surface area (cm^2)	40.8 ± 12.3	-0.2 ± 3.7	2.6 [2.3, 3.0]	40.8 ± 12.5	-0.2 ± 3.9	2.6 [2.3, 3.0]
Postural balance						
COP_{path} (cm)	77.0 ± 21.0	-1.7 ± 11.0	7.8 [7.0, 8.8]	76.6 ± 20.8	-1.6 ± 10.5	7.6 [6.7, 8.8]
COP_{area95} (cm^2)	7.4 ± 4.7	-0.5 ± 4.2	3.0 [2.7, 3.4]	7.4 ± 4.7	-0.2 ± 4.1	2.9 [2.6, 3.4]
Foot-strike						
Angle (˚)	7.9 ± 9.4	0.2 ± 3.0	2.1 [1.9, 2.4]	7.9 ± 9.6	0.1 ± 3.1	2.2 [2.0, 2.6]
Speed						
(m/s)	3.3 ± 0.4	0.01 ± 0.1	0.09 [0.08, 0.10]	3.3 ± 0.4	0.001 ± 0.1	0.1 [0.1, 0.1]

$^{+}$ Compares Trial 1, Trial 2, and Trial 3 within sessions.

* Compares all consecutive trials (Trial 1 to Trial 9) across the three sessions (3 x 3 trials).

Table 4. Inter-session means, changes in mean and TE (typical error). Values are mean ± standard deviations.

	Inter-session					
	Individual trials[+]			Session average[*]		
	Mean ± SD	Change in mean	TE [90% CI]	Mean ± SD	Change in mean	TE [90% CI]
Plantar pressure						
Bilateral						
Left foot (%)	49.0 ± 7.6	0.1 ± 7.1	5.0 [4.5, 5.7]	49.0 ± 6.7	0.008 ± 5.3	3.8 [3.1, 4.8]
Right foot (%)	51.0. ± 7.6	-0.1 ± 7.1	5.0 [4.5, 5.7]	51.0. ± 6.6	-0.1 ± 5.2	3.7 [3.1, 4.7]
Left foot mean pressure (kPa)	28.0 ± 11.7	-1.1 ± 6.47	4.6 [4.1, 5.2]	28.0 ± 11.4	-1.1 ± 4.5	3.2 [2.6, 4.0]
Right foot mean pressure (kPa)	23.9 ± 7.7	-0.9 ± 4.6	3.2 [2.9, 3.7]	23.9 ± 7.3	-0.9 ± 2.5	1.8 [1.5, 2.3]
Left foot surface (cm^2)	35.2 ± 11.4	-0.4 ± 3.8	2.7 [2.4, 3.0]	35.2 ± 11.4	-0.4 ± 2.3	1.6 [1.3, 2.1]
Right foot surface (cm^2)	41.2 ± 12.1	-0.04 ± 4.2	3.0 [2.7, 3.4]	41.2 ± 12.0	-0.2 ± 2.1	1.5 [1.3, 1.9]
Individual						
Left foot mean pressure (kPa)	25.8 ± 8.3	-0.7 ± 5.5	3.9 [3.5, 4.4]	25.8 ± 7.6	-0.2 ± 2.9	2.0 [1.7, 2.6]
Right foot mean pressure (kPa)	28.9 ± 8.8	-0.1 ± 6.6	4.7 [4.2, 5.3]	28.9 ± 8.1	-0.1 ± 3.7	2.6 [2.2, 3.3]
Left foot surface area (cm^2)	42.8 ± 12.6	-0.4 ± 4.6	3.2 [2.9, 3.7]	42.0 ± 13.5	-0.4 ± 2.6	1.9 [1.5, 2.4]
Right foot surface area (cm^2)	40.8 ± 12.3	-0.7 ± 3.6	2.5 [2.3, 2.9]	40.8 ± 12.3	-0.7 ± 2.5	1.8 [1.5, 2.2]
Postural balance						
COP$_{path}$ (cm)	76.6 ± 20.6	-4.0 ± 10.4	7.4 [6.6, 8.4]	76.6 ± 19.8	-4.0 ± 6.0	4.3 [3.5, 5.4]
COP$_{area95}$ (cm^2)	7.4 ± 4.7	0.01 ± 4.1	2.9 [2.6, 3.3]	7.4 ± 4.1	-0.1 ± 2.3	1.6 [1.4, 2.1]
Foot-strike						
Angle (˚)	7.9 ± 9.4	-0.2 ± 3.1	2.2 [1.9, 2.5]	7.9 ± 9.4	-0.2 ± 1.7	1.2 [1.0, 1.5]
Speed						
(m/s)	3.3 ± 0.4	0.01 ± 0.1	0.10 [0.09, 0.11]	3.3 ± 0.4	-0.01 ± 0.1	0.07 [0.06, 0.09]

[+] Compares Trial 1 across sessions, Trial 2 across sessions, and Trial 3 across sessions

[*] Compares the average of Trial 1, Trial 2, and Trial 3 across sessions.

Table 5. Intra-session intraclass coefficient and coefficient of variations with [90% CI] for plantar pressure, postural balance, foot-strike and speed.

	Intra-session			
	3 trials$^+$		**9 trials***	
	ICC [90% CI]	CV [90% CI]	ICC [90% CI]	CV [90% CI]
Plantar pressure				
Bilateral				
Left foot (%)	0.63 [0.52, 0.73]	**9.4 [8.5, 10.8]**	0.62 [0.47, 0.77]	**9.9 [8.7, 11.4]**
Right foot (%)	0.62 [0.50, 0.72]	**9.1 [8.2, 10.4]**	0.62 [0.46, 0.77]	**9.4 [8.3, 10.9]**
Left foot mean pressure (kPa)	0.87 [0.82, 0.91]	17.3 [15.4, 20.0]	0.87 [0.80, 0.93]	18.0 [15.8, 21.0]
Right foot mean pressure (kPa)	0.85 [0.79, 0.90]	13.3 [11.9, 15.4]	**0.90 [0.84, 0.95]**	11.3 [10.0, 13.2]
Left foot surface (cm^2)	**0.96 [0.94, 0.97]**	**7.9 [7.1, 9.1]**	**0.96 [0.93, 0.98]**	**8.2 [7.3, 9.5]**
Right foot surface (cm^2)	**0.94 [0.91, 0.96]**	**8.5 [7.6, 9.7]**	**0.95 [0.92, 0.97]**	**8.1 [7.1, 9.4]**
Individual				
Left foot mean pressure (kPa)	0.84 [0.78, 0.89]	13.8 [12.3, 15.9]	0.87 [0.80, 0.93]	12.9 [11.3, 15.0]
Right foot mean pressure (kPa)	0.74 [0.65, 0.82]	16.0 [14.3, 18.5]	0.76 [0.63, 0.86]	16.3 [14.3, 19.1]
Left foot surface area (cm^2)	**0.95 [0.93, 0.97]**	**8.5 [7.6, 9.8]**	**0.95 [0.92, 0.97]**	**8.8 [7.7, 10.2]**
Right foot surface area (cm^2)	**0.96 [0.94, 0.97]**	**7.2 [6.5, 8.3]**	**0.96 [0.94, 0.98]**	**7.3 [6.5, 8.5]**
Postural balance				
COP_{path} (cm)	0.87 [0.82, 0.91]	**9.1 [8.1, 10.4]**	0.88 [0.81, 0.93]	**9.2 [8.1, 10.7]**
COP_{area95} (cm^2)	0.60 [0.48, 0.71]	44.3 [39.0, 51.9]	0.62 [0.46, 0.77]	44.5 [38.5, 52.8]
Foot-strike				
Angle (°)	**0.95 [0093, 0.97]**	26.4 [23.7, 30.1]	**0.95 [0.92, 0.97]**	28.2 [25.0, 32.6]
Speed				
(m/s)	**0.96 [0.94, 0.97]**	**2.8 [2.5, 3.1]**	**0.96 [0.94, 0.98]**	**2.7 [2.4, 3.2]**

$^+$ Compares Trial 1, Trial 2, and Trial 3 within sessions.

* Compares all consecutive trials (Trial 1 to Trial 9) across the three sessions (3 x 3 trials).

Bold indicates CV (< 10%) and an excellent ICC (ICC ≥ 0.90).

Table 6. Inter-session intraclass coefficient and coefficient of variations with [90% CI] for plantar pressure, postural balance, foot-strike and speed.

	Inter-session			
	Individual trials[+]		**Session average[*]**	
	ICC [90% CI]	CV [90% CI]	ICC [90% CI]	CV [90% CI]
Plantar pressure				
Bilateral				
Left foot (%)	0.57 [0.44, 0.68]	10.2 [9.2, 11.7]	0.71 [0.51, 0.84]	**8.2 [6.8, 10.6]**
Right foot (%)	0.56 [0.43, 0.67]	**9.9 [8.9, 11.3]**	0.71 [0.53, 0.85]	**7.6 [6.3, 9.7]**
Left foot mean pressure (kPa)	0.85 [0.79, 0.89]	18.7 [16.7, 21.6]	**0.93 [0.88, 0.97]**	12.0 [9.9, 15.6]
Right foot mean pressure (kPa)	0.83 [0.76, 0.88]	14.2 [12.7, 16.4]	**0.95 [0.90, 0.97]**	**7.7 [6.4, 9.9]**
Left foot surface (cm^2)	**0.95 [0.93, 0.97]**	**8.2 [7.3, 9.4]**	**0.98 [0.97, 0.99]**	**4.9 [4.1, 6.3]**
Right foot surface (cm^2)	**0.94 [0.91, 0.96]**	**8.7 [7.8, 10.0]**	**0.98 [0.97, 0.99]**	**4.7 [3.9, 6.0]**
Individual				
Left foot mean pressure (kPa)	0.72 [0.63, 0.80]	21.4 [19.1, 24.8]	**0.94 [0.89, 0.97]**	**8.2 [6.8, 10.5]**
Right foot mean pressure (kPa)	0.75 [0.67, 0.83]	16.2 [14.5, 18.4]	**0.90 [0.82, 0.95]**	**9.3 [1.7, 11.9]**
Left foot surface area (cm^2)	**0.95 [0.92, 0.96]**	**8.8 [7.9, 10.1]**	**0.98 [0.97, 0.99]**	**4.9 [4.1, 6.3]**
Right foot surface area (cm^2)	**0.95 [0.93, 0.97]**	**6.2 [5.6, 7.1]**	**0.98 [0.96, 0.99]**	**5.6 [4.7, 7.2]**
Postural balance				
COP_{path} (cm)	0.88 [0.83, 0.92]	**8.8 [7.9, 10.1]**	**0.96 [0.93, 0.98]**	**4.9 [4.1, 6.3]**
COP_{area95} (cm^2)	0.61 [0.49, 0.71]	43.5 [38.3, 50.9]	0.84 [0.72, 0.92]	22.8 [18.7, 29.9]
Foot-strike				
Angle (°)	**0.95 [0.93, 0.97]**	27.3 [24.5, 31.1]	**0.99 [0.97, 0.99]**	15.2 [12.6, 19.3]
Speed				
(m/s)	**0.95 [0.93, 0.96]**	**3.2 [2.8, 3.6]**	**0.97 [0.95, 0.99]**	**2.4 [2.0, 3.0]**

[+] Compares Trial 1 across sessions, Trial 2 across sessions, and Trial 3 across sessions

[*] Compares the average of Trial 1, Trial 2, and Trial 3 across sessions.

Bold indicates CV (< 10%) and an excellent ICC (ICC ≥ 0.90).

	Intra-session (3 trials)$^{+}$			Intra-session (9 trials)*		
	Rear-foot	**Mid-foot**	**Fore-foot**	**Rear-foot**	**Mid-foot**	**Fore-foot**
Rear-foot	**92**	3	1	**122**	4	1
Mid-foot	1	**7**	1	4	**9**	1
Fore-foot	0	3	**18**	0	3	**24**
κ	0.88 [0.81, 0.94]			0.87 [0.81, 0.93]		
Agreement (%)	92.9 [87.6, 96.1]			92.3 [87.8, 95.3]		

$^{+}$Compares Trial 1, Trial 2, and Trial 3 within sessions.
*Compares all consecutive trials (Trial 1 to Trial 9) across the three sessions (3 x 3 trials).

	Inter-session (individual)$^{+}$			Inter-session (average)*		
	Rear-foot	**Mid-foot**	**Fore-foot**	**Rear-foot**	**Mid-foot**	**Fore-foot**
Rear-foot	**91**	4	0	**31**	1	0
Mid-foot	3	**6**	2	1	**3**	0
Fore-foot	1	1	**18**	0	0	**6**
κ	0.85 [0.78, 0.93]			0.92 [0.83, 1.01]		
Agreement (%)	91.3 [85.8, 94.9]			95.2 [85.0, 99.0]		

$^{+}$Compares Trial 1 across sessions, Trial 2 across sessions, and Trial 3 across sessions.
*Compares the average of Trial 1, Trial 2, and Trial 3 across sessions.

Figure 9. Contingency tables of intra-session and inter-session agreement of foot-strike pattern classification with linear weighted kappa (κ) and 90% confidence intervals [lower, upper].

4. Discussion

The findings from this study suggest that test-retest reliability of plantar pressure (PP) distribution, centre of pressure (COP), and 2D video-based assessments of foot-strike pattern (FSP), foot-strike angle, and running speed are relatively similar for both intra-session and inter-session measures. More specifically, PP distribution measures exhibited fair to good intra-session and inter-session reliability for relative pressure-load and mean pressure with suboptimal CV values (≥ 10%), with only surface contact area exhibiting excellent reliability and acceptable CV values. COP_{path} and COP_{area95} reliability was fair to good, with COP_{path} demonstrating CV values under 10% and relatively small TE compared to COP_{area95}. FSP reliability demonstrated excellent linear weighted kappa (κ) and high percentage agreement statistics within and between sessions. Furthermore, foot-strike angle and speed both demonstrated excellent reliability, although errors of ~2˚ were typical in foot-strike angles. Finally, deriving speed measures from 2D video analysis was valid when compared to the use of timing lights.

4.1 Plantar pressure

Surface area was the most reliable PP distribution measure assessed for both intra-session and inter-session reliability. Intra-session surface area in a bilateral stance demonstrated excellent reliability when considering either three or nine trials, and was higher than previously reported[25,54] (ICC 0.94 to 0.96 versus 0.56 to 0.74[27] and 0.85 to 0.90[80]). In agreement with other studies[25,54], inter-session reliability of bilateral surface area was excellent.

Relative pressure-load and mean pressure values demonstrated similar ICC values to that previously reported for intra-session reliability[27]; however, inter-session reliability was lower in our study compared to previous investigations[25,54]. No study has yet reported the reliability of individual foot surface area and mean pressure, with our data indicating excellent intra-session and inter-session reliability for these measures.

Methodological procedures could potentially explain differences in reliability outcomes between this study and existing reliability literature. The cohort in this study completed PP distribution measures in their habitual running shoes, whereas both previous reliability studies[25,54] assessed barefoot PP distribution. Research has shown differences in the way feet and shoes interact with the ground[95-97]; hence, knowledge on the reliability of both barefoot and shod assessments is of value.

4.2 Postural balance

COP_{area95} reliability was lower than previously reported in an eyes closed condition with a narrow stance for both intra-session (ICC 0.60 versus 0.710[56] and 0.79 to 0.92[72]) and inter-session measures (ICC 0.61 versus 0.83[57,71,73]). Individual trial inter-session COP_{path} reliability was also lower than previously reported[60] (ICC 0.88 versus 0.94); however, when comparing the inter-session COP_{path} average the results are similar. Intra-session reliability was higher than that previously reported[56] in an eyes closed, narrow stance condition.

COP_{path} reliability was higher than COP_{area95} across both intra-session and inter-session measures with COP_{area95} demonstrating a CV of ~44%. The relatively large CV suggests high variability in the area measure across trials, with the CV value likely inflated due to the small mean COP_{area95} value and inter-subject variability (7.4 ± 4.7 cm^2). Clinicians and researchers may need to use caution when making inferences based on changes in COP_{area95}; instead changes in COP_{path} may provide more reliable information.

One earlier study[57] demonstrated differences in COP_{area95} and COP_{path} reliability between "normal" and narrow stance conditions, with COP_{area95} more reliable in a normal stance and COP_{path} more reliable in a narrow stance. Although outside the scope of this study, understanding the reliability of these measures in different stance conditions could aid in the interpretation of postural balance changes.

4.3 Running gait

Overall, FSP reliability was similar to that previously reported[29,51,81]. However, only one[29] of these three reliability studies reported intra-session and inter-session reliability. Intra-session reliability was in line with that reported by Damsted et al.[29] (κ = 0.87 to 0.88 versus 0.84 to 0.88[29]), whilst inter-session FSP reliability was higher in the present study (κ = 0.85 to 0.92 versus 0.66 to 0.69[29]).

The sampling rate in the current study could potentially account for the differences in foot-strike pattern reliability measures, with the present study using a lower sampling frequency (240 Hz) than previous reliability studies (300 Hz[29] and 550 Hz[81]). For accurate comparisons between studies, a standardised sampling rate is required.

Reliability of foot-strike angle was not concurrently assessed alongside FSP classification in previous studies[29,51,81]. Intra-session and inter-session foot-strike angle reliability was excellent; however, the CV was suboptimal (15.18 to 28.25%). The limited foot-strike angle range of 26˚ (minimum: -3˚ fore-foot; maximum: 23˚ rear-foot) in our population could potentially explain the suboptimal CV as the TE (2.5˚) represents a large absolute variation. These foot-strike angle reliability measures could assist in determining worthwhile changes in foot-strike angle in clinical and research settings. Our study demonstrates that a change in foot-strike angle of at least 2˚ should be the minimum change required to infer an actual change in this measure within a given participant.

Although average running speed across all sessions (3.3 ± 0.4 m/s) was higher than previously reported (2.8 ± 0.4 m/s)[29,51], the reliability of speed was not determined in previous reliability studies[29,51,81] due to the use of treadmills. Identifying self-selected running speed with Siliconcoach Pro software demonstrated excellent intra-session and inter-session reliability. Furthermore, a high correlation was demonstrated between Siliconcoach Pro and the timing lights, suggesting Siliconcoach Pro is an accurate and valid software to assess running speed from 2D videos.

4.4 Limitations

One limitation of this study was the decision to test participants with their shoes for all measurements. This decision was made to inform Chapter 4 where runners would be assessed pre- and post-race with their running shoes for enhanced functional relevance and due to time constraints. Also, the reliability of PF_{isom} could not be established due to technical issues with the data collection equipment. As such, future investigations are required to establish the reliability of measures from the novel PF_{isom} set-up.

5. Conclusion

The reliability of measures is important in both clinical and research settings to ensure accurate interpretation of results. In this study, test-retest reliability was determined for measures of plantar pressure (PP) distribution, centre of pressure (COP), video-assessment of foot-strike pattern (FSP), foot-strike angle and speed. The most reliable measures were: PP surface area, COP path length, FSP classification, foot-strike angle, and speed measures. Therefore, the use of these measures in future research studies and in clinical practice is recommended.

Chapter Three – Intra-rater and inter-rater reliability of overground running measures

This chapter appears in the same format as required by a peer-reviewed scientific journal where it has been submitted for publication consideration. Citation: Murray, L., Beaven, C.M., Hebert-Losier, K. (2018) Reliability of overground running measures from 2D video analyses in a field environment. Manuscript under review.

Abstract

BACKGROUND: Two-dimensional analyses of running are common in research and practice, and shown to be reliable when conducted on a treadmill. However, a considerable amount of running is preformed outdoors. Our aim was to determine the intra- and inter-rater reliability of 2D analyses of overground running in an outdoor environment.

METHODS: Two raters independently evaluated 155 high-speed videos (240 Hz) of overground running from a cohort of recreationally competitive runners on two occasions, 7 days apart. Foot-strike pattern (rear-foot, mid-foot, and fore-foot), foot-strike angle (°), and running speed (m/s) were extracted using a video analysis software. Reliability was assessed using weighted kappa (κ), percentage agreement, intra-class correlation coefficient (ICC), typical error (TE), and coefficient of variation (CV) statistics.

RESULTS: Foot-strike pattern (agreement = 99.4%, κ = 0.963) and running speed (ICC = 0.98, TE = 0.1 m/s, CV = 2%) demonstrated excellent relative and absolute reliability. Relative reliability of foot-strike angle was high (ICC = 0.88), but absolute reliability was suboptimal (TE = 2.50°, CV = 18%).

CONCLUSION: Two-dimensional analyses of overground running are reliable for quantifying foot-strike pattern, foot-strike angle, and running speed, although foot-strike angle errors of 2.5° are typical. Therefore, changes in foot-strike angles of less than 2.5° should be interpreted in caution in clinical settings, as this change might simply reflect measurement errors as opposed to actual changes in foot-strike pattern.

KEYWORDS: intra-rater, inter-rater, reliability, foot-strike pattern, foot-strike angle, running speed

1. Introduction

Running popularity is increasing, with over 5000 organised marathons and 2 million finishers per year since 2015 according to the Association of Road Racing Statisticians (http://www.arrs.net). The repetitive activation of the lower extremity muscles during running[1,115] and the cyclical nature of the activity has been linked to high injury rates[1,115], especially when combined with high vertical loading. Foot-strike is an important part of running biomechanics with the foot providing a solid base of support[2], absorbing and redistributing impact forces throughout the kinetic chain, and contributing to propulsion and balance during locomotion[1,2]. Foot-strike pattern in particular has been associated with an increased likelihood of certain types of running injuries[36]. For example, hip and knee injuries are two times more likely in rear-foot-strikers than fore-foot-strikers[36], while an increase in ankle and foot-related injuries is observed in fore-foot strikers[36,39].

Foot-strike pattern has also been suggested to change with running speed[33,100], with the odds of mid-foot or fore-foot striking relative to rear-foot striking increasing when running speed increases by 1 m/s in a cohort of runners with an average self-selected speed of 3.69 m/s[14] or when running speed exceed 5 m/s[5,6]. As running speed increases, the following changes in running gait tend to occur: total cycle time, absolute and relative duration of stance phase, and base of support decreases, and step length, relative duration of the swing phase, joint excursion, and cadence increase[1,2]. In laboratory and clinical settings, speed is generally determined and standardised using a treadmill[81]. The chosen assessment speed can either be absolute, relative, or self-selected, where self-selected can be based on habitual running speeds[29].

When assessing running gait overground, runners are often required to target a selected speed where a margin of error of ± 5% is deemed acceptable[110,111], or asked to run at a self-selected speed[14]. Both of these approaches require the monitoring of speed with some form of equipment. Photocells, global positioning systems, laser-based timing devices, and two dimensional (2D) video analyses are some of the most commonly used devices to monitor running speed in practical settings[116], with one advantage being their relative affordability compared to research-grade equipment. The standardisation or monitoring of running speed is important in terms of reproducibility of assessments and monitoring changes in runners.

The use of 2D video analyses in the field and during competitive event is common in sport science[13,15,18]; however, there is limited information on the reliability of measures of running speed in field-based settings. The reliability of foot-strike pattern and angle measures are also typically derived from treadmill-based analyses[29,51,81]. Within these settings, treadmills have been found to be reliable overall in terms of running gait analyses[29]. However, most runners train and compete outdoors, decreasing the validity and applicability of previous reliability studies for field-based assessments.

Given the common usage of 2D video analyses within research and clinical practice to analyse running gait and importance of overground running assessments, the aims of this study were to determine the intra- and inter-rater reliability of 2D video analyses of overground running in an outdoor environment. In particular, we aimed to examine the reliability of foot-strike pattern, foot-strike angle, and running speed.

2. Material and methods

2.1 Participants

Twenty-eight recreational runners (17 males, 11 females) who were participating in a 12-km organised race volunteered to participate in this study (**Table 7**). Inclusion criteria were: 18 years or over, free from any musculoskeletal or neurological injuries, and anticipated 12-km race times of 75 minutes or less (average race pace ≤ 6 min 15 s per km). Participants were recruited as part of a larger study on racing-induced fatigue with a pre-and-post race study design. Participants were recruited via electronic newsletters and emails sent by the race organisers, and on race day via pamphlets handed out at the registration desk and in vicinity of the data collection area. All participants wore their own running shoes for testing and were asked to run at their perceived race pace during assessment. All participants provided written informed consent prior to participation. The protocol was pre-approved by the Human Research Ethics Committee of the University of Waikato [HREC(Health)#11] prior to recruitment and complied with the Declaration of Helsinki.

Table 7. Participant and shoe characteristics. Values are means ± standard deviations.

	Male (*n* = 17)	**Female (*n* = 11)**	**Total (*n* = 28)**
Participant			
Age (y)	37.8 ± 12.6	33.6 ± 10.0	36.2 ± 11.7
Height (cm)	176.5 ± 6.8	165.8 ± 6.9	172.1 ± 8.6
Body mass (kg)	81.1 ± 8.0	60.6 ± 6.5	73.6 ± 12.5
Running experience (y)	9.2 ± 10.3	5.4 ± 3.9	7.6 ± 8.3
Runs (per week)	3.9 ± 1.6	3.2 ± 0.6	3.6 ± 1.3
12-km race times (min)	58.9 ± 10.1	69.5 ± 12.0	63.0 ± 11.9
Shoe			
Mass (g)	306.7 ± 28.1	251.5 ± 35.1	284.6 ± 41.0
Heel height (mm)	28.3 ± 5.8	26.8 ± 6.2	27.7 ± 5.9
Heel-to-toe drop (mm)	9.8 ± 1.9	9.7 ± 1.3	9.8 ± 1.7

2.2 Video recordings

The running gait of each participant was recorded pre- and post-race. Participants were asked to run three times at their perceived race pace (4.25 ± 0.71 m/s) through a 15-m level asphalt runway, with a 30-s walking rest between trials, for a total of 6 running trials for each participant (3 pre and 3 post) and 168 potentially eligible videos for intra- and inter-rater reliability assessment (28 participants x 2 sessions x 3 trials). The middle 5-m section of the runaway was demarcated by cones for video processing purposes. A digital camera (Cyber-shot DSC-RX10 II, Sony, Tokyo, Japan) sampling at 240 Hz was mounted on a 1-m high tripod in the sagittal plane, 6-m away from the running area to the right-hand side of participants. Foot-strike pattern, foot-strike angle, and running speed were determined using the video recordings. Due to the on-field nature of the data collection, 13 of the potentially eligible videos were not available for subsequent reliability assessment (i.e., time constraints linked with the start of the 12-km organised race, operator error, and obscured participants from bystanders). Hence, data analyses were performed on 155 video recordings.

2.3 Video processing

Siliconcoach Pro8 (The Tarn Group, Dunedin, NZ) was used to display each video recording frame by frame. The original video recordings were converted from MP4 to AVI format to ensure compatibility with the software. For each video, the foot-strike pattern and foot-strike angle for the right foot-strike nearest to the middle of the marked 15-m area was determined from the frame with the first clearly visible foot contact with the ground. Foot-strike pattern was classified based on part of the foot that made ground contact as either: rear-foot (first contact was the heel or rear third of the sole only), mid-foot (first contact was the mid-foot or entire sole), or fore-foot (first contact was the fore-foot or front half of the sole) following previously reported classification schemes[13,15]. Foot-strike angle was calculated as the line that joined the sole of the shoe from the point of first contact and the ground, wherein a positive angle represented rear-foot-striking, and a negative angle represented greater fore-foot-striking (Figure 10). Participant running speed was calculated based on the time taken to cover the mid 5-m section of the runway.

Figure 10. Foot-strike angle examples of rear-foot, mid-foot, and fore-foot.

2.4 Reliability

To investigate the reliability of measures extracted (i.e., foot-strike pattern, foot-strike angle, and running speed), a repeated-measures design was employed. Data were extracted from all eligible videos (n = 155) by two sport science graduates (LM, FS) on two separate occasions, 7 days apart. The two raters each had more than 2 years of practical experience in strength and conditioning and practical assessment, and were accustomed to observing and quantifying movement. Prior to data extraction, the raters were familiarised with the Siliconcoach Pro8 software using the manufacturer's online training resources. Furthermore, an internal data extraction protocol was developed and implemented through a series of internal training sessions to promote standardisation. The two raters were blinded to each other's measures, as well as to their previous measures when completing their second assessments. Intra-rater reliability was calculated by comparing Occasion 1 and Occasion 2 data from both raters; whereas inter-rater reliability was calculated by comparing Rater 1 and Rater 2 data from both occasions.

2.5 Statistical analyses

Mean and standard deviation (mean ± SD) values were computed to describe foot-strike angle and running speed data, whereas counts were used to describe foot-strike pattern data. Given that foot-strike pattern was a categorical variable with three levels (rear-foot, mid-foot, and fore-foot), linear weighted kappa (κ) with 90% confidence intervals were computed to quantify reliability. The agreement of the categorical ratings were interpreted as: ($\kappa < 0.40$), fair ($0.40 \geq \kappa < 0.60$), good ($0.60 \geq \kappa < 0.80$), and excellent ($\kappa \geq 0.80$)[50,51].

Foot-strike angle and speed data were analysed using a customisable statistical spreadsheet[114]. Intraclass correlation coefficients (ICC), typical error (TE), and coefficient of variation (CV) with 90% confidence intervals [lower, upper] were calculated to quantify the relative (ICC) and absolute (TE and CV) reliability of measures. For the purpose of interpreting the ICC[52], the relative reliability of measures was considered as: poor (ICC < 0.40), fair (0.40 ≥ ICC < 0.75), good (0.75 ≥ ICC < 0.90), and excellent (ICC ≥ 0.90). Absolute reliability was deemed acceptable when the CV was < 10%, as in common practice in sport and exercise science[53], and suboptimal when ≥ 10%. Paired *t* -tests were also carried out on the data to identify the presence of systematic bias, with statistical significance set at $p \leq 0.05$.

3. Results

Based on the 155 videos analysed, foot-strike pattern demonstrated excellent intra- and inter-rater reliability (**Figure 11**), with agreements of 99.4% [97.8, 99.9] and kappa values of 0.96 [0.92, 1.00]. Intra- and inter-rater absolute and relative reliability was excellent for running speed (**Table 8**). Although relative reliability for foot-strike angle was good (ICC = 0.88), absolute reliability was suboptimal with CVs of 17.6% (**Table 8**). A systematic bias was indicated between raters in terms of foot-strike angles with one rater rating (~1˚) higher than the other.

		Rater 1		
		Rear-foot	**Mid-foot**	**Fore-foot**
Rater 2	**Rear-foot**	**295**	0	0
	Mid-foot	0	**1**	1
	Fore-foot	0	0	**13**

		Occasion 1		
		Rear-foot	**Mid-foot**	**Fore-foot**
Occasion 2	**Rear-foot**	**295**	0	0
	Mid-foot	0	**1**	1
	Fore-foot	0	0	**13**

Figure 11. Contingency tables of inter-rater (above) and inter-rater (below) agreement of foot-strike pattern classification.

Table 8. Intraclass coefficient (ICC), typical error (TE), and coefficient of variation (CV) with 90% confidence intervals [lower, upper] for foot-strike angle and speed. Mean and standard deviation (mean ± SD) values for each rater and occasion are provided.

	Comparison[a]		**Statistics**			
	1 (raw units)	**2 (raw units)**	**TE (raw units)**	**CV (%)**	**ICC**	**p-value**
Foot-strike angle (˚)						
Intra-rater	13.9 ± 7.1	14.5 ± 7.4	2.5 [2.3, 2.7]	17.6 [16.5, 18.8]	0.88 [0.86, 0.90]	0.352
Inter-rater	15.2 ± 7.1	13.2 ± 7.4	2.5 [2.3, 2.7]	17.6 [16.5, 18.8]	0.88 [0.86, 0.90]	0.001*
Speed (m/s)						
Intra-rater	4.25 ± 0.71	4.24 ± 0.71	0.09 [0.08, 0.09]	2.08 [1.95, 2.23]	0.98 [0.98, 0.99]	0.835
Inter-rater	4.22 ± 0.70	4.28 ± 0.72	0.09 [0.08, 0.10]	2.13 [2.00, 2.28]	0.98 [0.98, 0.99]	0.276

[a] Intra-rater comparison: Occasion 1 vs Occasion 2; inter-rater comparison: Rater 1 vs Rater 2.
* Statistical significance $p < 0.05$.

4. Discussion

The findings from this study suggest that two-dimensional video analysis of overground running performed outdoors are reliable for quantifying foot-strike pattern, foot-strike angle, and running speed, although foot-strike angle errors of 2.5° are typical within and between raters. As such, researchers and clinicians should interpret foot-strike angle changes less than 2.5° with caution, as might reflect the measurement error as opposed to an actual change in foot-strike pattern.

4.1 Foot-strike patterns

Foot-strike pattern is an important running characteristic, with research demonstrating differences between foot-strike patterns in vertical of ground reaction force patterns[16], running biomechanics[16], and injury sites[117]. Our intra- and inter-rater reliability kappa values for foot-strike pattern classification (κ = 0.963) were higher than those previously reported from treadmill analyses[29,51,118]. Damsted et al.[29] reported kappa values for intra-rater agreement ranging from 0.63 to 0.69, and inter-rater agreement ranging from 0.41 to 0.53, whereas Pipkin et al.[51] reported an average intra-rater and inter-rater kappa value of 0.86 and 0.85. Bertelsen et al.[118] investigated inter-rater reliability of footstrike classification of participants running on a laboratory runway, reporting kappa values for the left side of 0.76 to 0.82 and for the right side of 0.85 to 0.92. Lower kappa values reported in all three studies compared to ours could be due to the higher number of categories used to classify foot-strike pattern, with researchers using five (heel, heel/mid-foot, mid-foot, mid-foot/fore-foot, and fore-foot[29]) or four (heel, rear-foot, mid-foot, and fore-foot[51]; and rear-foot, mid-foot, fore-foot, and asymmetry[118]). Indeed, Damsted et al.[29] anticipated a lower reliability in foot-strike classification than previously reported[118] due to their use of five categories rather than the more typical three to four. However, these authors believed that their 5-level classification had a greater clinical relevance as they considered subtle differences in foot-strike patterns[29]. The present study used three foot-strike classifications due its greater ease of use and common application in practice and research[13-16,30], with the current results suggesting that foot-strike classification is more reliable with a lower number of categories. Of the videos analysed, the raters only disagreed upon one occasion, with the disagreement spanning only one category (mid-foot – fore-foot). Closer inspection of the disagreement between raters revealed differences in the video frame identified as initial foot-ground contact which would contribute to their disagreement in foot-strike classification.

The high level of agreement for foot-strike classification in our study compared to others might result from our relatively homogenous sample, with 95% of videos being associated with a rear-foot strike as opposed to approximately 75% in previous reliability studies[51,81]. Each participant contributed between 3 to 6 videos to our reliability analysis, which could contribute to the homogeneity of our sample; however, this is somewhat of a lesser concern given our interest in the rater reliability measures. Furthermore, our higher proportion of rear-foot strikers is deemed to accurately reflect the recreationally competitive running population, where approximately 90% of individuals have been reported to be rear-foot stikers[15].

Running speed has been demonstrated to change the proportion of foot-strike patterns at speeds of 4.9 m/s or higher[14,33,100]. Thus, due to the average speed in the present study (~ 4.2 m/s) we would anticipate a greater proportion of rear-foot strikers. Although we would expect an increased likelihood of mid-foot and fore-foot strikers within our study compared to the work of Cheung et al.[14] (with an average running speed of 3.69 m/s), this was not observed. These findings show that recreational runners will generally adopt a rear-foot foot strike and supports existing literature suggesting that runners utilising a pace of less than 5 m/s are most likely to adopt a rear-foot strike.

4.2 Foot-strike angle

The relative intra and inter-rater reliability for foot-strike angle was good (ICC = 0.88), but the typical error of 2.5°was associated with a rather large CV (17.6%). The large CV here is likely a reflection of the foot-strike angle range in our population that was limited to 42° [minimum value of -11° (fore-foot) and maximum of +31° (rear-foot)]. The foot-strike angle range is similar to previous research[32,100] which shows the foot-strike angles demonstrated in this study are in the range of others reported in literature. The foot-strike angle reliability measures derived herein can be useful in clinical and research settings to determine worthwhile changes in foot-strike angle. There is a growing amount of gait re-training literature attempting to influence foot-strike patterns[119]. Our study demonstrates that a change in foot-strike angle of at least 2.5° should be the minimum change required to infer an actual change in this measure, whereas a change of 2.5° or less would fall within the typical measurement error range. Similar to the foot-strike index proposed by Altman et al.[32], we concur that the use of the foot-strike angle provides a more objective and quantifiable indicator of foot-strike pattern than using categories.

4.3 Running speed

Many running studies and clinical assessment of running gait use treadmills[29,51], which enables speed to be controlled and standardised across participants or testing occasions. Overground running speed is not as easy to standardise or quantify in the field, particularly when allowing individuals to self-select their running speed. A previous review of the literature suggests that video-based quantification of speed is valid and reliable[116], with almost perfect agreement between speed computed from an off-the-shelf video camera and photocells[120] and no significant differences between 2D video analyses and laser measurement devices[121]. Excellent test-retest reliability has been reported for average speed of participants within a 3-m area using a 50- and 100 Hz camera, with single measure ICC values of 0.954 and 0.947, respectively[121]. However, Harrison et al. examined participant rather than inter-rater reliability of the video analyses. Our research adds to the body of literature by identifying that both intra- and inter-rater reliability of running speed from 2D videos collected outdoors demonstrates excellent relative reliability (ICC = 0.98) with low typical errors (0.09 m/s, ~2%).

5. Conclusion

The intra- and inter-rater reliability of foot-strike pattern identification during overground running using a high-speed video setup in an outdoor environment is highly reliable (κ = 0.963). Foot-strike angle and running speed using the same 2D video analysis also showed good to excellent relative reliability (ICC = 0.88 and 0.98, respectively), although errors of 2.5° are typical in foot-strike angle. Therefore, changes in foot-strike angles of less than 2.5° should be interpreted in caution in clinical settings, as might simply reflect measurement errors as opposed to actual changes in foot-strike pattern.

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AUTHORS' CONTRIBUTIONS: LM carried out the identification and classification of the videos, performed the statistical analysis and helped to draft the manuscript; CMB participated in the conception, its design and coordination; KHL participated in the conception, its design and coordination, performed statistical analysis and helped to draft the manuscript.

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Chapter Four – The effects of running a 12-km race on neuromuscular performance measures and running gait

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Abstract

There is an increasing number of individuals participating in organised races, with few studies undertaken in such settings. Running involves repetitive movements and cyclical activation of lower extremity muscles, with foot-strike pattern and fatigue proposed as contributing factors of running-related injury incidence. Our aims were to investigate the effects of running a 12-km race on plantar pressure distribution, postural balance, foot-strike pattern, and plantar-flexion isometric strength-endurance measures, as well as to compare actual versus anticipated race finishing times and foot-strike patterns. Twenty-four recreationally competitive runners (15 males, 9 females) completed the following tests immediately before and after a 12-km organised race: (1) plantar pressure distribution in self-selected bilateral stance; (2) 30-seconds eyes-closed feet-together postural balance; (3) self-selected running speed and foot-strike angle; and (4) peak plantar-flexion isometric strength-endurance force normalised to body weight. In-race foot-strike patterns were also assessed at the 3-km and 10-km mark. Post-race left and right foot plantar pressure distribution, postural balance measures, and plantar-flexion isometric strength-endurance force measures significantly differed from pre-race measures. Participants predicted their race finishing times relatively well, but not their foot-strike patterns. No meaningful change in foot-strike angle or pattern was observed pre- to post-race, or between the 3-km to the 10-km mark. Running a 12-km race influenced several neuromuscular measures, confirming racing-induced fatigue in our recreationally competitive runners. However, these alterations did not lead to observable changes in foot-strike patterns, indicating that this measure might not be appropriate for quantifying fatigue in recreationally competitive runners.

Keywords: balance, centre of pressure, isometric strength, foot strike, plantar pressure

1. Introduction

Over the years, there has been an increase in the number of organised racing events worldwide and the number of participants entering these events (http://www.arrs.net). Mass participation in running events is positive given that running has many health-enhancing benefits, including a decreased risk of all-cause mortality and cardiovascular death[122]. However, running involves repetitive impact forces and activation of the lower extremity muscles[1], with the incidence of lower extremity injuries sourced from a literature review of individuals running 5 km or more per training or race reported to range from 19.4 to 79.3%[123]. Foot-strike pattern and fatigue are some of the risk factors that have been associated with an increased likelihood of overuse lower extremity injuries in runners[36]. It has been suggested that with each type of foot-strike pattern, certain types of injuries are more likely. For example, rear-foot strikers are two times more likely to sustain hip and knee injuries than fore-foot strikers; but conversely, they may be less susceptible to Achilles tendinopathies and foot pain[36].

Neuromuscular fatigue from sustained exercise results in a quantifiable decline in performance, such as a reduction in maximal force or power output[124]. Marathon running has been shown to decrease maximal sprint running, five-jump, drop-jump, and isometric knee torque performance measures; while running 2 h on a treadmill, decreased the maximal voluntary isometric contraction and level of activation of the plantar-flexor muscles[125]. With fatigue of select lower extremity muscles, there is a shift in work load to less fatigued muscles and kinematic adaptations to maintain performance levels and moderate running impact loads to avoid injuries[21]. More specifically, selective fatigue of the ankle plantar-flexors and dorsi-flexors has been associated with a decrease in ankle dorsiflexion at initial contact, at mid-stance, and during the swing phase of running[21]. With running fatigue, however, certain changes in running biomechanics may increase the risk of overuse injury because of a decreased ability of the musculoskeletal system to attenuate impact forces[126].

Other changes in running kinetics and kinematics reported for exhaustive treadmill tests lasting from 16 to 50 minutes[3,126,127] and following a marathon[24] include a decrease in peak and mean plantar pressure loads at the toes. A review on the effects of fatiguing protocols on balance measures also found that the intensity, duration, and type of exercise affect postural sway[128]. Incremental treadmill exercise has been shown to elicit greater balance impairments than incremental cycle ergometer exercise[128] presumably due to a more selective fatigue of the lower extremity muscles involved with upright stance during a locomotion-based exercise.

Amongst runners, the most commonly self-reported foot-strike pattern is a mid-foot one[30,31]. However, self-reported foot-strike pattern accuracy is relatively low, with previous studies reporting agreement levels ranging between 43.5 to 68.3%[28,30], with the highest agreement seen in rear-foot strikers wearing traditional shoes (90.9% agreement between actual and self-reported foot-strike)[28]. Running experience could potentially contribute to errors in self-reported foot-strike patterns, as collegiate cross-country runners have demonstrated a 13% higher self-reported foot-strike accuracy compared to recreational runners[30].

Injury prevention is a key component in the maintenance of physical activity throughout life. Being able to determine any shifts in plantar pressure distribution, balance ability, running biomechanics, and force production due to running-induced fatigue may provide an insight into injury prevention strategies and appropriate pre-conditioning methods for runners. Most of the existing running literature has been conducted within laboratory settings on a treadmill. While such studies contribute to our knowledge on running, most running occurs outside of laboratory environments. Thus, our aims were to investigate the effect of running a 12-km race on plantar pressure distribution, postural balance, foot-strike, and plantar-flexion isometric strength-endurance measures in recreationally competitive runners. A secondary aim was to compare expected to actual race finishing times and foot-strike patterns.

2. Methods

2.1 Participants

Twenty-four recreationally competitive runners (15 males, 9 females) volunteered to participate (**Table 9**). Inclusion criteria were 18 years or over, free from any musculoskeletal or neurological injuries, and anticipated 12-km race finishing time of ≤ 75 minutes (pace ≤ 6 min 15 s per km). Participants were recruited via electronic newsletters and emails sent by the race organisers, and on race day via pamphlets handed out at registration and in vicinity of the data collection area. All participants provided written informed consent prior to participation. The protocol was approved by the Human Research Ethics Committee of the University of Waikato [HREC(Health)#11] and complied with the Declaration of Helsinki.

Table 9. Participant and shoe characteristics. Values are means ± standard deviations and medians (1st quartile, 3rd quartile).

	Male (*n* = 15)	**Female (*n* = 9)**	**Total (*n* = 24)**
Participant			
Age (y)	39.4 ± 11.2	31.5 ± 7.57	36.5 ± 11.2
Height (cm)	176.2 ± 6.2	164.3 ± 6.4	171.6 ± 8.5
Body mass (kg)	81.1 ± 8.0	60.6 ± 6.5	73.6 ± 12.5
Runs (per week)	3.5 (3.0, 5.3)	3.0 (3.0, 3.5)	3.0 (3.0, 4.0)
Running experience (y)	6 (2, 12)	5 (2, 10)	5 (2, 10)
Shoe			
Mass (g)	306.5 ± 29.5	251.5 ± 35.1	283.3 ± 41.7
Heel height (mm)	28.0 ± 6.0	26.8 ± 6.2	27.5 ± 6.0
Heel-to-toe drop (mm)	9.8 ± 2.0	9.7 ± 1.3	9.8 ± 1.7

Prior to the 12-km race, participants completed a baseline questionnaire that included their self-reported foot-strike pattern (rear-foot, mid-foot, or fore-foot) and expected race finishing time. Participants were familiarised with the testing procedures and each apparatus was zeroed before every trial. Plantar pressure distribution, postural balance, foot-strike pattern, and plantar-flexion isometric strength-endurance were tested sequentially, with participants wearing their own running shoes throughout testing. Immediately following the race, the same tests were performed. Participants median ratings of perceived exertion post-race on a 20-point Borg's scale was 17 (interquartile range: 15 to 18). The actual 12-km race finishing time for each participant was obtained from the official racing results posted by the race organisers.

2.2 Plantar pressure distribution

Plantar pressure was collected using the footscan® entry level USB2 platform (150 Hz sampling frequency) and gait 7 software (RSscan International, Belgium). Participants were asked to stand in the middle of the platform and then walk in place for a few seconds before stopping in a self-selected comfortable usual stance position[25,54], remaining as still as possible looking straight ahead with their arms by their side. Once in a stable position, static plantar pressure distribution was recorded as per the manufacturer's recommendations. The software was subsequently used to extract the relative pressure (%) distributed into anterior-posterior and left-right areas.

2.3 Postural balance

Postural balance was assessed using an AMTI AccuGait Optimized force plate sampling at 150 Hz and Balance Clinic software version 2.03.00 (Advanced Mechanical Technology Incorporated, Watertown, MA, USA). Participants were instructed to stand in the middle of the force plate with their feet together (toes and heels touching) and arms by their side, and then to remain as still as possible with their eyes closed. Once the participants were in the desired testing position for 3 seconds, 30 seconds of data were recorded. No verbal feedback was provided during the measurement time. The Balance Clinic Software was subsequently used to extract the centre of pressure path length (COP_{path}, cm) and area of the 95th percentile ellipse (COP_{area95}, cm^2), which encompassed 95% of the centre of pressure data points for the 30-second trial.

2.4 Pre- and post-race foot-strike pattern and angle

To assess foot-strike pattern pre- and post-race, a 15-m runway was delineated using cones on a level asphalt terrain. A digital camera (Cyber-shot DSC-RX10 II, Sony, Tokyo, Japan) sampling at 240 Hz was mounted on a 1-m high tripod in the sagittal plane, 6-m away from the running area to the right-hand side of participants. Participants were asked to run at their perceived race pace through the 15-m area. Each participant completed three running trials pre-race (4.3 ± 0.5 m/s) and post-race (4.2 ± 0.6 m/s, paired *t*-test $p = 0.2024$), with a 30-second walking rest between trials. Siliconcoach Pro version 8 software (The Tarn Group, Dunedin) was used to assess foot-strike pattern and angle of the right foot-strike occurring nearest to the mid portion of the 15-m runway (i.e., frame with the first clearly visible contact of the right foot with the ground). Foot-strike pattern was classified based on which part of the foot made ground contact first as either rear-foot (first contact was the heel or rear third of the sole only), mid-foot (first contact was the mid-foot or entire sole), or fore-foot (first contact was the fore-foot or front half of the sole) as described by Hasegawa et al.[13]. Foot-strike angles were measured as the line joining the sole of the shoe from the point of first contact and the horizontal plane of the running surface, wherein positive angles represented more pronounced rear-foot striking, and negative angles represented more pronounced fore-foot striking. The average foot-strike angle and most common foot-strike pattern from the three trials pre-race and post-race was used for data analyses.

2.5 In-race foot-strike pattern and angle

In-race foot-strike patterns and angles were investigated in vicinity of the 3-km and 10-km mark of the race on level asphalted sections of the course. A digital camera (Cyber-shot DSC-RX10 II, Sony, Tokyo, Japan) was mounted on a 1-m high tripod 3.5-m away from the road (approximately 6-m away from the main running area) to the right-hand side of runners. A sampling frequency of 120 Hz was used to allow continuous data recording in the race environment. To identify participants, study identification numbers were written with permanent markers on participants’ right lower leg.

2.6 Plantar-flexion isometric strength-endurance

To assess plantar-flexion isometric strength-endurance, participants stood on two dual-axis portable force plates (PASCO, Roseville, CA) sampling at 500 Hz that were positioned under a squat rack. Participants stood under a 20 kg Olympic barbell and were instructed to 'push as hard as possible' upwards against the barbell for 10 seconds using their calf muscles to exert force into the ground, keeping their knees straight. The task was isometric, as the barbell could not move upwards as was pushed against two safety bars positioned at shoulder height. The height of the barbell was standardised to allow the bar to rest on participants' shoulders while allowing a slight lift of the heels from the ground during the exertional task. Participants warmed-up for the maximal trial by completing a trial at 50 and 70% of maximal effort. When participants felt ready, the maximal trial was completed. The PASCO Capstone Software version 1.4 was used to extract peak force normalised to body weight (%BW).

Due to time constraints and the on-field experimental nature of our study, only one trial was conducted for all tests, except for the running trials where typical performance across three trials was extracted. A second trial for the balance and plantar pressure distribution was allowed if participants moved their arms or feet during testing; however, no participants required a second trial. Furthermore, no *a priori* sample size computations were preformed given the on-field nature of the experiment. Due to the eminent start of the race, three participants were unable to complete the plantar-flexion isometric strength-endurance test. Hence, pre- and post- race comparisons for this particular test are from 21 rather than 24 participants.

2.7 Statistical analysis

Mean and standard deviation (SD) values were computed for all variables to describe the data, except for non-parametric data where median and interquartile range (IQR) values are reported. Comparisons of pre-to-post means were performed using a customisable statistical spreadsheet and inferential statistics were calculated[114]. Magnitude-based inferential statistics were calculated using between-participant pre-race SD values, with 0.20 SD indicating the smallest worthwhile difference in means, except for foot-strike angle which was set to 2.5˚ (based on prior test-retest data[129]). Magnitudes of the standardised effect (ES) were interpreted using the following thresholds: *trivial* ($ES < 0.2$), *small* ($0.2 \leq ES < 0.6$), *moderate* ($0.6 \leq ES < 1.2$), and *large* ($ES \geq 1.2$). An effect was deemed clear if its 90% confidence interval [upper, lower] did not overlap the thresholds for *small* positive and *small* negative effects (i.e., 5%). Variables were log-transformed to reduce bias arising from non-uniformity of error and used for interpreting all statistical comparisons, except for foot-strike angle where log-transformation was not appropriate. Paired *t*-tests were also undertaken to verify statistical significance, which was set at $p < 0.05$. The 3-km and 10-km foot-strike angles were compared using the same statistical approaches. The levels of agreement and their 90% confidence intervals between pre- and post-race, 3-km and 10-km, and perceived and actual foot-strike patterns were computed using the Wilson score method incorporating continuity correction[130]. Kappa statistics on these data could not be computed due to an underrepresentation of mid-foot and fore-foot strikers.

3. Results

Participants completed the 12-km race in 61 ± 8 min, which was significantly faster than their anticipated finishing times of 63 ± 9 min (-2 ± 4 min, $P = 0.0426$). However, this difference between participants' anticipated and actual finishing times was deemed to be trivial based on the ES (-0.15 [-0.28, -0.02]).

3.1 Pre- versus post 12-km race

Following the race, there were clear and significant changes in most measures compared to pre-race values, except for anterior and posterior plantar pressure distribution and foot-strike angles (**Table 10**). Changes in both balance variables (COP_{path} and COP_{area95}) were *large*, whilst the ES related to the change in plantar pressure distribution and plantar-flexor isometric strength-endurance was *moderate* and *small*, respectively. Changes in foot-strike angle from pre- (16.7 ± 6.1°) to post-race (17.2 ± 5.0°) were *trivial*, with all participants being classified as rear-foot strikers across testing sessions.

3.2 3-km versus 10-km

No significant difference (*P* = 0.5703) was observed between the 3-km (9.9 ± 4.9°) and 10-km (10.6 ± 3.1°) marks in terms of foot-strike angle, with the mean change of 0.7 ± 4.3˚ being clearly trivial (ES: 0.14 [-0.15, 0.04]). All participants were rear-foot strikers at both time points, with the exception of one runner who demonstrated a mid-foot pattern at the 3-km mark and a rear-foot pattern at the 10-km mark (agreement: 95.8% [80.4, 99.7]).

3.3 Expected versus actual foot-strike pattern

Overall, all 24 participants were rear-foot strikers based on pre-, post-, and in-race measures (**Table 11**). Only 13 participants correctly identified themselves as rear-foot strikers (54.2% [36.0, 71.4]).

Table 10. Postural balance, plantar pressure distribution, plantar-flexion isometric strength-endurance, and foot-strike angle measures pre and post 12-km organised race (n = 24). Values are means ± standard deviations. The magnitudes of clear effects are reported.

	Pre	**Post**	**Change**	**ES [90% CI]**	**MBI**
Balance					
COP_{path} (cm)	80.5 ± 19.0	98.8 ± 25.7	18.2 ± 21.3	0.85 [0.53, 1.17]	*large**
$\text{COP}_{\text{area95}}$ (cm^2)	6.2 ± 3.2	11.9 ± 10.4	5.7 ± 8.9	0.94 [0.58, 1.29]	*large**
Plantar pressure					
Anterior (%)	52.3 ± 6.9	54.2 ± 7.0	1.9 ± 5.0	0.25 [-0.01, 0.50]	unclear
Posterior (%)	47.7 ± 6.9	45.8 ± 7.0	-1.9 ± 5.0	-0.28 [-0.52, -0.04]	unclear
Left (%)	55.2 ± 5.5	52.0 ± 5.0	-3.2 ± 5.0	-0.58 [-0.90, -0.26]	*small**
Right (%)	44.8 ± 5.5	48.0 ± 4.9	3.2 ± 5.0	0.55 [0.25, 0.85]	*small**
Plantar-flexion strength (*n* = 21)					
Force (BW)	2.1 ± 0.5	1.9 ± 0.4	-0.2 ± 0.3	-0.42 [-0.60, -0.24]	*small**
Foot-strike					
Angle (°)	16.7 ± 6.1	17.2 ± 5.0	0.5 ± 4.3	0.10 [-0.13, 0.33]	*trivial*

Abbreviations: CI, confidence interval; ES, effect size; MBI, magnitude-based inference.

*Paired t-test $p < 0.05$. An effect size was clear when its 90% confidence interval did not overlap the thresholds for *small* positive and *small* negative effects.

Table 11. Pre-race, post-race, 3-km mark, 10-km mark, and self-reported foot-strike patterns of participants (n = 24).

	Pre-race	Post-race	3-km	10-km	Self-reported
Rear-foot	24	24	23	24	13
Mid-foot	0	0	1	0	8
Fore-foot	0	0	0	0	3

4. Discussion

Running a 12-km race resulted in observable changes in postural balance measures (COP_{path} and COP_{area95}), left and right foot plantar pressure distribution, and plantar-flexion isometric strength-endurance. These neuromuscular changes suggest racing-induced fatigue in our recreationally competitive runners. Despite quantifiable declines in postural balance and plantar-flexion isometric strength-endurance, self-selected foot-strike angle did not meaningfully change and might not be an appropriate indicator of fatigue in runners, particularly in habitual rear-foot strikers.

4.1 Plantar pressure distribution

Plantar pressure distribution did not change significantly between anterior and posterior areas of the foot. Previous research has shown that a greater proportion of runners rear-foot strike at the 32-km mark of a marathon compared to the 10-km mark[15], and that with running-induced fatigue, there is a decrease in plantar pressure loads at the toes[3]. We hence expected an increase in the relative posterior plantar pressure load supporting these previously reported changes to a more rear-foot strike pattern and decreased toe pressure. The lack of anterior to posterior change in plantar pressure distribution in our study might have several explanations, including the fact that all our participants were rear-foot strikers and demonstrated comparable foot-strike angles pre- and post-race and between the 3-km and 10-km mark of the race. Furthermore, the plantar pressure distribution was taken under a static condition rather than a dynamic one. That said, we did observe a meaningful decrease of 3.2 ± 5.0% in the relative plantar pressure distributed under the left foot of our runners, with a corresponding increase under the right foot. These findings somewhat contrast with a previous study conducted on experienced recreational marathon runners[131] in which no significant changes in peak or mean plantar pressure between the dominant and non-dominant feet were observed when contrasting pre-race, in-race, and post-race measures, although, the dominant foot was favoured throughout the race. We did not seek information relating to foot dominance or quantified average and peak plantar loads; hence, direct comparisons with Hohmann et al.[131] is difficult.

Plantar pressure is most commonly assessed under dynamic conditions[132,133], with few studies assessing static plantar pressure distribution[25,54]. We measured plantar pressure specifically in a static stance with participants' running shoes as it was the most feasible in our field environment. Our data indicates that there may be a shift in how runners distribute their weight in a static stance with exercise-induced fatigue. The shift we observed from left to right could potentially reflect compensatory strategies of muscles to shift workload to less fatigued muscles or reflect the influence of running on cambered roads[134]. However, it is unknown how long the observed redistribution in plantar pressure loads from left to right is likely to last, whether they are course-dependent and reproducible, or what the clinical implications might be. The simplistic segmentation of the foot into anterior-posterior and left-right quadrants in the present study makes it hard to directly compare with existing literature in which the foot is segmented anywhere from three to eleven segments[131-133,135,136].

4.2 Balance

Postural balance measures worsened following the 12-km race in our recreationally competitive runners, with *large* and significant increases in both COP_{path} and $\text{COP}_{\text{area95}}$ post-race compared to pre-race. A review of the literature on postural control highlights how balance impairments post-exercise are likely of multi-factorial origin, and can result from fatigue, hyperventilation, functional deterioration of mechanoreceptors and proprioceptors, dehydration, and hyperthermia[128]. Previous studies involving exhaustive running[137,138] corroborate deterioration in postural stability measures, with larger impairments in eyes-closed rather than eyes-open conditions[137]. Although investigating the time-course of impairments was not within the scope of our study, postural impairments subsequent to aerobic and anaerobic exercise protocols have been shown to return to baseline values within thirteen minutes[139].

4.3 Foot-strike pattern

A study of 936 recreational runners in the Manchester City Marathon and Half-Marathon observed rear-foot striking in 88.9% of the runners at the 10-km mark[15]. Of the 286 participants who completed the full marathon, the proportion of rear-foot strikers increased from 87.8% at 10-km to 93.0% at 32-km[15]. The same study provided evidence that running speed and performance alters foot-strike pattern, with the fastest runners utilising a mid-foot strike. However, other research indicate no differences in foot-strike pattern between self-selected comfortable and competitive running speeds[140]. In our study, participants were rear-foot strikers in all but one 3-km observation, with no meaningful change in self-selected foot-strike angle between pre-race and post-race measures or 3-km and 10-km in-race measures. In rear-foot strikers, changes in foot-strike angle and pattern might not be an appropriate indicator of fatigue. However, two fatiguing studies conducted by Kellis et al.[21] and Christina et al.[141] observed a decrease in dorsiflexion angle at initial ground contact whilst running on a treadmill, resulting in a greater area of the heel contacting the ground[142]. Such changes were not readily observed in our population, which might be due to the on-field nature of our experiment and 2D as opposed to 3D methods used to quantify foot-strike angle.

Although not statistically compared, an observable difference between the in-race (10.3 ± 3.5°) and out-of-race (17.0 ± 5.1°) foot-strike angles was noted, with the data suggesting a less acute rear-foot strike angle in-race. While the difference could be due to running speed, in-race speed (3.28 m/s) was slower than what was recorded pre- and post-race (4.25 m/s); hence, our change in foot-strike angle is opposite to findings of increasing mid-foot or fore-foot strike at faster self-selected running speeds[14]. A more plausible explanation to the difference between in-race and out-of-race foot-strike angles could be the data capture under semi-controlled conditions under the observation of an examiner versus under natural conditions with no clear knowledge of being examined. The presence of a testing device can also alter running gait, with differences in hip and ankle kinematics when running over an embedded force plate, two different types of plantar pressure mats, and no measuring device[143]. Hip flexion was significantly greater at foot-strike in the Footscan condition compared to no device and ankle plantar-flexion was significantly greater in the Matscan and Footscan conditions than no device, with an embedded force plate causing the least deviations from uninhibited running[143]. These findings suggest that running gait is altered when participants are aware of force-sensing measurement devices, which might be extended to awareness of being recorded.

4.4 Perceived versus actual foot-strike pattern:

A little over half of our participants accurately predicted their foot-strike pattern prior to the 12-km race. The results of the present study are similar to those reported by Bade et al.[30] who noted that 43.5% of recreational runners correctly identify their foot-strike patterns prior to running on a treadmill. However, Bade et al.[30] used reflective markers on the participants' shoes to determine foot-strike angle as opposed to 2D video analyses or observations, which then informed their foot-strike pattern. Goss et al.[28] used a similar foot-strike pattern identification procedure to the current study, with experienced physical therapists identifying foot-strike pattern with 2D video. In that instance, self-reporting of foot-strike pattern was accurate in 68.3% of cases. The higher accuracy in the Goss et al.[28] study can be attributed to the authors using two foot-strike patterns (rear-foot and anterior foot-strike) compared to the three used in this study. Overall, these data confirm that self-assessment of foot-strike pattern by runners is subject to error and requires objective quantification for valid inferences.

4.5 Perceived versus actual running performance:

Trivial differences between perceived and actual finishing times were observed in the current study. Participants in our study were able to predict their finishing times relatively well, which could be due to most participants running times 3 [3,4] a week and for 5 [2, 10] years, despite considering themselves as "recreational" runners. Our inclusion criteria for the study included an anticipated 12-km race finishing time of 75 minutes or less and could contribute to their ability to predict finishing times. Earlier studies have reported positive significant correlations between predicted and actual race finishing times for races ranging from 1 mile to 10 km[144]. Compared to other research[145], our cohort was better able to accurately predict their finishing time. Many factors can influence running performance prediction, e.g., injury, illness, social (running with a friend), running experience, and emotional responses to negative outcomes.

4.6 Plantar-flexion isometric strength-endurance

The present study provides novel findings regarding plantar-flexion isometric strength-endurance post-race, with a clear decline in strength measures of approximately 10%. Peak plantar-flexion torque has been reported to decline after 8.8 ± 3.4 min of fatiguing cycling exercise performed on an ergometer at 17.8 ± 1.4 km/h[136]. The findings of the current study add to the existing literature on running providing evidence that peak plantar-flexion force decreases after a 12-km race. Unilateral heel raises preformed to fatigue with either 0°, 30°, or 45° of knee flexion[44,46] are one of the most common methods used in clinical settings to quantify plantar-flexor strength. However, performing this test takes time and does not reflect bilateral plantar-flexion performance. In contrast, our bilateral isometric plantar-flexion strength-endurance test was able to detect fatigue in both plantar-flexors immediately post-race through a 10 second protocol. Alterations in plantar-flexor function might in part explain the declines we observed in postural control, as previously shown that inducing fatigue of the plantar-flexors leads to alterations in postural control in healthy males[146], with values returning to baseline 20 minutes following muscular fatigue[146].

4.7 Limitations

One limitation of this study is the relatively small sample size (*n* = 24); however, the testing was conducted in an ecologically valid environment with all individuals measured prior to the 12-km race returning for testing following the race. Post-hoc power analyses indicated we had sufficient power to detect differences with 80% power at a 5% significance level for COP_{path}, COP_{area95}, and left – right PP distribution. Due to time constraints, we elected to record one measure for most tasks, which does not account for intra-subject variability in performance or extensive familiarisation. As such, there may have been a learning effect from pre- to post-race that we are currently unable to quantify. Given that any learning effect in this study would likely have improved performance post-race, we may have shown a greater change pre- to post-race had participants undergone a more extensive familiarisation session. Finally, since only one post-race testing session was undertaken following the race finish (typically 2 to 5 minutes after crossing the finish line), the persistence of the observed changes remains unknown.

5. Conclusion

Running a 12-km race influenced several neuromuscular measures, confirming racing-induced fatigue in our recreationally competitive runners. Despite quantifiable declines in postural balance and plantar-flexion isometric strength-endurance, self-selected foot-strike angle did not meaningfully change and might not be an appropriate indicator of fatigue in recreational runners. Our findings corroborate the importance of plantar-flexion isometric strength-endurance in racing events, and that postural control is altered in fatigued runners. Tracking postural control measures over time may be useful in the monitoring of training loads and recovery in runners. Finally, although our population of runners were able to predict their race finishing times with a relatively high accuracy, their self-reported foot-strike patterns were not representative of their actual foot strike patterns in nearly 50% of cases. Objectively quantifying foot strike pattern rather than self-reported is recommended in research and practice prior to making any inferences related to this gait characteristics.

Chapter Five – Discussion and Conclusion

1. Summary

A systematic review of reliability articles relating to measures of plantar pressure (PP) distribution, centre of pressure (COP), video-based assessment of foot-strike pattern (FSP), and plantar-flexion isometric strength-endurance (PF_{isom}) was completed with each article quality assessed for methodological quality. Of the 43 studies quality appraised in this thesis, only 21% were deemed to be of high methodological quality (≥ 75% COSMIN score). This finding highlighted the need for higher quality methodological reliability studies to be undertaken to make stronger inferences about the reliability of these measures to track changes in healthy cohorts. Hence, two reliability studies were undertaken to assess these measures in both laboratory and on-field settings. Measures of PP surface area, COP path length, FSP, foot-strike angle, and running speed were found to be the most reliable. Lastly, a study measuring the effects of a 12-km race observed quantifiable declines in COP and PF_{isom} measures post-race, confirming racing-induced fatigue and impaired postural control and plantar-flexion isometric strength-endurance in recreationally competitive runners.

2. Practical implications

From this thesis, several practical implications can be suggested. In a clinical setting, measures of PP distribution surface area and COP path length may enable more accurate interpretations of change than measures of relative pressure-loads, PP mean pressure, and COP_{area95}. Changes in foot-strike angles of less than 2.5° should be interpreted with caution in clinical settings, as changes of this magnitude might simply reflect measurement errors or individual variability as opposed to actual changes in foot-strike pattern. Objectively quantifying FSP rather than using self-reported patterns can also be recommended in research and practice given that the latter is subject to error. Running a 12-km race influenced several neuromuscular measures, confirming racing-induced fatigue in recreationally competitive runners. Despite quantifiable declines in postural balance and plantar-flexion isometric strength-endurance, self-selected foot-strike angle did not meaningfully change and might not be an appropriate indicator of fatigue in recreational runners. Our findings corroborate the importance of plantar-flexion isometric strength-endurance in racing events, and that postural control is altered in fatigued runners. Tracking postural control measures over time may be useful in the monitoring of training loads and recovery in runners.

3. Strengths

The findings of this thesis add to existing literature on COP measures derived from a force plate, static PP distribution on a pressure mat, observed and self-reported FSP, foot-strike angle, speed, and PF_{isom}. The systematic review and accompanying quality appraisal highlights the need for higher quality articles to enable findings to be directly compared. To address this need, a test-retest reliability study provided insight into which measures were most reliable. This thesis also highlighted the need for standardisation across 2D video-based assessments of running gait to enable stronger inferences across studies. Finally, testing was conducted in an ecologically valid environment in Chapter Four, with all individuals measured prior to the 12-km race returning for testing following the race.

4. Limitations

A limitation of this thesis is the relatively small sample sizes for both test-retest reliability (n = 21) and the quantification of neuromuscular changes post a 12-km race (n = 24). In the latter case, post-hoc power analyses indicated sufficient power to detect differences with 80% power at a 5% significance level for COP_{path}, COP_{area95}, and left – right PP distribution; however, underpowered for anterior – posterior PP distribution, PF_{isom}, and foot-strike angle. The time constraints associated with the 12-km race also had its limitation, with only one measure pre- and post-race being obtained in a shod condition, which did not allow us to account for intra-subject variability in performance or provide extensive familiarisation. Another limitation of this thesis was the inability to quantify the reliability of PF_{isom} due to technical issues with the data collection equipment.

5. Future research

Higher methodological reliability studies could assist clinicians and researchers make stronger inferences about changes in healthy cohorts for measures of static PP distribution, COP, video-based 2D analyses, and PF_{isom} in an upright stance. Furthermore, tracking these measures over time could be useful in the monitoring of training loads and recovery in runners. The reliability of measures from the novel PF_{isom} set-up used in this thesis still requires investigation, as does the time-course of the observed neuromuscular changes post-race in our cohort of runners.

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Appendix 1. Ethics application approval

Human Research Ethics Committee & Human
Research Ethics Committee (Health)
Julie Barbour
Telephone: +64 7 837 9336
Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

31 October 2016

Kim Herbert-Losier
University of Waikato Adams Centre for High Performance,
52 Miro St,
Mount Maunganui 3116

Dear Kim

HREC(Health)#11 'The influence of a 12-km race on footstrike, running gait, balance, and calf muscle function, the effect of running on functional changes with age'

Your updated ethics application for the research project titled 'The influence of a 12-km race on footstrike, running gait, balance, and calf muscle function, the effect of running on functional changes with age' forwarded in your of 25th October 2016, has been approved.

All the very best with your research.

Regards,

Prof Mark Apperley

Acting Chairperson

University of Waikato Human Research Ethics Committee (Health)

Appendix 2. Ethics amendment

Human Research Ethics Committee & Human
Research Ethics Committee (Health)
Julie Barbour
Telephone: +64 7 837 9336
Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

24th July 2017

Kim Herbert-Losier
University of Waikato Adams Centre for High Performance,
52 Miro St,
Mount Maunganui 3116

Dear Kim,

HREC(Health)#11 'The influence of a 12-km race on footstrike, running gait, balance, and calf muscle function, the effect of running on functional changes with age'

We understand that you would like to add a named student researcher, Lauralee Murray (ID1327731), to your project. Lauralee will use project data for the purpose of writing her Masters Thesis. This request is approved.

Please contact the committee if you wish to make further changes to your project as it unfolds, quoting your application number HREC(Health)2016#11), with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee (Health)

Appendix 3. COSMIN study characteristics

Study design	Population	Protocol and conditions	Equipment and measures		Reliability of selected measures	
PP						
Izquierdo-Renau et al. [54] T-RT	23 female, 17 male 28.78 ± 11.43 y 68.24 ± 13.53 kg 1.68 ± 0.09 m	5 trials Stand centre of the platform, looking ahead, arms positioned naturally either side of the body, simulate gait walking in place for 15 s **Time between sessions:** 7 days	**Equipment:** S-Plate platform, max 100 Hz **Measures:** Peak pressure: L, R Mean pressure: L, R Weight each foot Total foot contact Foot contact: L, R	ICC [1,1] and [1,k], CV (%) **Intra-session, session 1:** Peak Pressure: 0.73, 8.85% Mean Pressure: 0.82, 6.37% BW left: 0.82, 9.18% BW right: 0.80, 8.62% Total contact area: 0.91, 6.28% Contact area left: 0.85, 8.88% Contact area right: 0.85, 8.43%	**Intra-session, session 2:** Peak Pressure: 0.69, 8.43% Mean Pressure: 0.86, 4.88% BW left: 0.85, 8.40% BW right: 0.82, 8.10% Total contact area: 0.95, 4.77% Contact area left: 0.90, 7.68% Contact area right: 0.88, 7.64%	ICC [1,k] **Inter-session:** Peak Pressure: 0.86 Mean Pressure: 0.93 BW left: 0.97 BW right: 0.97 Total contact area: 0.97 Contact area left: 0.96 Contact area right: 0.96
Vallejo et al. [25] T-RT	36 male, 20 female 47.7 ± 16.7 y 71.6 ± 13.5 kg 167 ± 8.1 cm	5 x 30 s Simulate gait by walking in place for 15 s, stood in a natural manner, looked straight ahead, maintained arms close to body **Time between sessions:** 3-20 days apart (9.90 ± 4.11 days)	**Equipment:** EPS-Platform 60 Hz, Foot Checker v.40 for Windows **Measures:** BW% Surface area BW% bilateral fore-foot BW% bilateral rear-foot BW% fore-foot BW% rear-foot Mean pressure	ICC [1,1] and [1,k], CV (%) **Intra-session, session 1:** %BW left: 0.68, 4.8% %BW right: 0.68, 4.0% Mean Pressure left: 0.78, 8.5% Mean Pressure right: 0.85, 6.9% Surface area left: 0.67, 12.2% Surface area right: 0.56, 12.3%	**Intra-session, session 2:** %BW left: 0.70. 4.9% %BW right: 0.70, 4.2% Mean Pressure left: 0.8, 7.1% Mean Pressure right: 0.88, 6.4% Surface area left: 0.74, 10.3% Surface area right: 0.74, 9.1%	ICC [1,k], SEM (%, kPa or cm^2) **Inter-session** %BW left: 0.948, 0.9 %BW right: 0.948, 0.9 Mean Pressure left: 0.979, 2.4 Mean Pressure right: 0.977, 2.5 Surface area left: 0.949, 8.2 Surface area right: 0.932, 8.6

Study design	Population	Protocol and conditions	Equipment and measures	Reliability results of selected measures	
COP					
Bauer et al. [57] T-RT	21 male, 42 female 78.74 ± 6.65 y 1.61 ± 0.11 m	**Protocol:** 3 x 30 s, 2 min rest No shoes, heads erect, arms resting at sides, instructions to maintain balance. **Conditions:** Heels 2 cm apart, 30˚ between feet, EO, EC narrow stance EO, EC	**Equipment:** SATEL force plate, 40 Hz, customized software **Measures:** Area 95 Length ML sway AP sway	ICC [2,1] (95% CI): **EO, normal stance:** Area 95: 0.873 (0.803, 0.920) Length: 0.885 (0.825, 0.9527) ML sway: 0.899(0.844, 0.936) AP Sway: 0.843 (0.763, 0.900) **EO, narrow stance:** Area 95: 0.878 (0.814, 0.922) Length: 0.886 (0.826, 0.927) ML sway: 0.841(0.758, 0.899) AP Sway: 0.907 (0.858, 0.941)	**EC, normal stance:** Area 95: 0.945 (0.917, 0.965) Length: 0.933 (0.891, 0.959) ML sway: 0.918 (0.874, 0.948) AP Sway: 0.926 (0.874, 0.956) **EC, Narrow stance:** Area 95: 0.710 (0.553, 0.818) Length: 0.945 (0.915, 0.966) ML sway: 0.933 (0.896, 0.958) AP Sway: 0.946 (0.915, 0.967)
Bauer et al. (2010) [58] T-RT	22 female, 8 male 77.23 ± 6.81 y	**Protocol:** 3 x 30 s, 2 min rest No shoes, heads erect, arms at sides, instructed to maintain balance. **Conditions:** 2 cm heel distance and 30° between feet, EC and EO Narrow stance, EC and EO	**Equipment:** SATEL force plate, 40 Hz, SATEL software **Measures:** Trajectory: ML, AP	ICC [2,1] (99% CI), CV (%) **EO, trajectory, normal stance:** ML: 0.706 (0.349, 0.880), 28% AP: 0.655 (0.258, 0.864), 24% **EO, trajectory, narrow stance:** ML: 0.846 (0.658, 0.937), 20% AP: 0.828 (0.619, 0.930), 19%	**EC, trajectory, normal stance:** ML: 0.806 (0.570, 0.921), 25% AP: 0.792 (0.539, 0.914), 19% **EC, trajectory, narrow stance:** ML: 0.906 (0.791, 0.962),21% AP: 0.853 (0.675, 0.940), 26%
Carpenter et al. [59] T-RT	20 male, 29 female	**Protocol:** 3 x 120 s, 120 s seated rest Stand quietly on a force plate with feet positioned comfortably in a box defined by dimensions equal to their foot length (feet traced), arms hanging at sides, head normal face-forward position, eyes on target approx. 2 m away	**Equipment:** 20 Hz **Measures:** Mean power frequency Mean position	ICC **EO, mean position:** ML 15 secs: 0.75 AP 15 secs: 0.86 ML 30 secs: 0.79 AP 30 secs: 0.87	ML 60 secs: 0.84 AP 60 secs: 0.89 ML 120 secs: 0.85 AP 120 secs: 0.91

Chang et al.[63] T-RT Rater	15 male, 15 female 24.4 ± 3.9 y 171.9 ± 8.3 cm 68.8 ± 11.3 kg	**Protocol:** 1 x 20 s Hands on hips, double-leg stance – both feet on the ground with medial malleoli in contact, EC **Conditions:** firm and foam, double-leg, single-leg and tandem **Time between sessions:** 7 days	**Equipment:** Inverted Wii Balance Board affixed to OR6-7-2000 force plate, customised software in LabVIEW, Quickcam Pro 5000, 3 raters **Measures:** Path length	ICC [2,1] **EC, Test-retest:** Force plate: 0.66 Wii Balance board: 0.68 BESS raters: No value **EC, Inter-rater:** No value	Pearson correlation (*r*) **EC, Validity** (compared to force plate): WBB: 0.99 BESS: No value
Chiari et al. T-RT	6 female, 6 male	**Protocol:** 10 x 50 s, 60 s rest Arms by sides, look at a target at eye level 3 m away, stand in comfortable stance **Conditions:** EO, EC	**Equipment:** Bertec 4060-08 force platform, 20 Hz **Measures:** Mean velocity Area ellipse 95% Fractal dimension Centroidal frequency	ICC **EO:** Mean velocity: 0.83 Area 95: 0.58	**EC:** Mean velocity: 0.87 Area 95: 0.70

Clark et al.[147] T-RT	10 male, 20 female 23.7 ± 5.6 y 1.68 ± 0.09 m 6.38 ± 15.20 kg	**Protocol:** 3 x 30 s, 15 s rest Hands placed on hips and remain as still as possible, 60 s rest between device or task **Conditions:** Feet together: EO, EC Single limb, EO, EC Random order of tasks and devices **Time between sessions:** Within 2 weeks, at least 24 h apart	**Equipment:** ATMI Model OR6-5, mounted flush with the lab floor, 40 Hz WBB – custom-written software Labview 8.5, 40 Hz **Measures:** Total path length	ICC [2,1] (95% CI), SEM (cm), MDC **EO, length:** FP: 0.86 (0.71, 0.93), 2.2, 14.5% WBB: 0.66 (0.20, 0.85), 4.0, 27.9% **Between device:** Day 1: 0.77 (0.46, 0.90) Day 2: 0.78 (0.54, 0.90)	**EC, path length:** FP: 0.94 (0.87, 0.97), 4.0, 16.1% WBB: 0.91 (0.80, 0.96), 6.6, 24.5% **Between device:** Day 1: 0.89 (0.71, 0.95) Day 2: 0.88 (0.67, 0.95)
Corriveau et al. (2000)[148] T-RT	4 female, 3 male 68.6 ± 4.3 y	**Protocol:** 11 x 120 s, 5 min rest between trials Stood quietly, look straight ahead, arms comfortable at sides, EO	**Equipment:** 2 x AMTI force plates, 20 Hz, 3 OPTOTRAK senosrs, 20 Hz, Matlab 5.1 **Measures:** Root mean square COP-COM: AP, ML	ICC [2,1] (95% CI), MMDC **EO, COP-COM, single trial:** ML: 0.64 (0.44, 0.92) AP: 0.79 (0.58, 0.99) **EO, COP-COM, mean 4 trials:** ML: 0.90, 16mm AP: 0.94, 10mm	

Corriveau et al. (2001) [56] T-RT Rater	18 female, 27 male 70.5 ± 6.0 y 69.6 ± 11.3 kg 1.59 ± 2.50 m	4 x 120 s, 5 min between trials, 10 min between condition Double leg stance, feet pelvis width (feet traced), max of 14˚ hip external rotation to minimize discomfort, flat-soled shoes, look straight ahead with their head erect, arms in a comfortable position hanging at their sides **Conditions:** EO, EC **Time between sessions:** Intra-rater: 30 min Inter-rater & T-RT: 3- 7 days	**Equipment:** 2 x AMTI force plates, 20 Hz, MATLAB 5.1, 2 raters **Measures:** Root square mean COP-COM: AP, ML	ICC [2,1] (95% CI) **EO, COP-COM, mean:** Rater ML: 0.66 (0.45, 0.80) Rater AP: 0.92 (0.87, 0.96) T-RT ML: 0.72 (0.43, 0.83) T-RT AP: 0.91 (0.85, 0.95)	**EC, COP-COM, mean:** Rater ML: 0.79 (0.64, 0.88) Rater AP: 0.92 (0.86, 0.96) T-RT ML: 0.72 (0.53, 0.83) T-RT AP: 0.90 (0.83, 0.94)
Doyle et al. [66] T-RT	10 female, 20 male 23 ± 5 y 1.75 ± 0.09 m 71 ± 12 kg	3 x 10 s Modified CTSIB, Feet position based on height: 21, 25 or 30cm width, arms by sides **Conditions:** EO, EC, rigid and foam Randomized order of testing	**Equipment:** Fitness Technologies force plate, 100 Hz **Measures:** Range of sway: AP, ML Peak sway velocity Total excursion area: AP, ML Fractal dimension: AP, ML	ICC [2,1] **EO:** Range of sway ML: 0.71 Range of sway AP: 0.43 Peak sway velocity ML: 0.29 Peak sway velocity AP: 0.12 Total excursion area: 0.49	**EC:** Range of sway ML: 0.51 Range of sway AP: 0.65 Peak sway velocity ML: 0.19 Peak sway velocity AP: 0.58 Total excursion area: 0.95

Geurts et al. [67]	Group 1: 4 male, 4 female 44.3 ± 19.7 y Group 2: 4 male, 4 female 24.9 ± 2.4 y	Group 1: 3 x 20 s, 1 min rest Group 2: 2 x 30 s, 1 min rest Feet against a foot frame (medial sides of heels 8.4 cm apart, toeing-out angle 9˚, hands clasped lightly behind their back **Conditions:** Group 1: EO, blurred vision, EC (with dark glasses) Group 2: single task, dual task **Time between sessions:** Biweekly	**Equipment:** Force plate: Group 1: 100 Hz, Group 2: 30 Hz **Measures:** Root mean square amplitude: ML, AP Mean frequency: AP, ML Root mean square velocity: AP, ML Peak-to-peak amplitude: AP, ML	Mean CV % **EO, group 1:** RMS, ML: 39% RMS, AP: 37% Mean frequency: 31% Mean frequency: 36% RMS velocity, ML: 35% RMS velocity, AP: 24%	**EC, group 1:** RMS, ML: 36% RMS, AP: 33% Mean frequency: 30% Mean frequency: 32% RMS velocity, ML: 35% RMS velocity, AP: 20%
Golriz et al. [27] T-RT	16 male, 14 female 30.5 ± 7.2 y 25.6 ± 5.5 BMI	5 x 60 s, 1 min rest (allowed to sit) Feet shoulder width apart (traced), shoeless, arms to the side in a comfortable position, distribute weight evenly on both feet while breathing normally, look straight ahead at an X on opposite wall (2 m away at eye level) **Time between sessions:** 5 min	**Equipment:** Midot posture scale analyser QPS 200, 200 Hz **Measures:** COP mean velocity Average COP location Sway area Body weight %: L, R	ICC [3,k] (95% CI) **EO, velocity:** 1 rep: 0.19 (-0.75, 0.62) 2 reps: 0.83 (0.65, 0.92) 3 reps: 0.95 (0.90, 0.98) 4 reps: 0.97 (0.94, 0.99) 5 reps: 0.92 (0.84, 0.96) **EO, location:** 1 rep: 0.53 (-0.01, 0.78) 2 reps: 0.92 (0.84, 0.96) 3 reps: 0.91 (0.81, 0.96) 4 reps: 0.93 (0.85, 0.97) 5 reps: 0.94 (0.88, 0.97)	**EO, sway area:** 1 rep: 0.06 (-1.02, 0.56) 2 reps: 0.47(-0.13, 0.75) 3 reps: 0.63 (0.28, 0.82) 4 reps: 0.68 (0.33, 0.85) 5 reps: 0.83 (0.64, 0.92)

Hill et al. [61] T-RT	17 subjects 69.5 ± 7.3 y	9 x 25 s, 1 min rest shoes removed, safety harness around waist, feet 12 cm apart or feet together, looking at picture in front, hands by sides **Conditions:** EO: Feet apart, feet together, Sharpened Romberg, stable platform, and rotating platform at 50% and 100% speed **Time between sessions:** 7 days	**Equipment:** Chattecx Balance System **Measures:** COP	ICC [2,1], CV (%) **EO:** Feet apart: 0.55, 17% Feet together: 0.27, 19%
Kitabayashi et al. T-RT	108 male, 112 female 20.1 ± 1.6, 19.6 ± 1.4 y 173.3 ± 5.9, 161.0 ± 5.8 cm 67.0 ± 7.9, 54.3 ± 6.1 kg	3 x 1 min, 1 min rest Barefoot, arms comfortably at sides **Conditions:** EO	**Equipment:** Anima stabilometer G5500, 20 Hz **Measures:** Path length Area Velocity: X, Y axis Distribution of amplitude Power spectrum Vector	ICC **EO:** Path length: 0.97 Area circle: 0.90 Velocity X-axis: 0.96 Velocity Y-axis: 0.96

Lafond et al. [69] T-RT	4 female, 3 male 67.9 ± 4.3 y 65.6 ± 17.5 kg 161 ± 12 cm 9 x 120 s, 5 min rest	Double-leg stance pelvis width stance (feet traced), EO, look straight ahead, head erect, arms at sides in comfortable position	**Equipment:** 2 x Model OR6-5 force plates, 20 Hz **Measures:** Root mean square Sway area COP range COP mean velocity Mean power frequency Median power frequency	ICC [2,1] (95% lower bound): **EO, Sway area:** 30 secs: 0.22 60 secs: 0.47 120secs: 0.41 (0.16) **EO, COP range:** ML 30secs: 0.44 AP 30 secs: 0.29 ML 60 secs: 0.57 AP 60 secs: 0.38 ML 120secs: 0.62 (0.35) AP 120secs: 0.52 (0.25)	**EO, COP mean velocity:** ML 30 secs: 0.87 AP 30 secs: 0.73 ML 60 secs: 0.90 AP 60 secs: 0.77 ML 120 secs: 0.94 (0.85) AP 120secs: 0.83 (0.64)
Letz et al. T-RT	15 female, 15 male 23 – 60 y 2 x 60 s	No shoes, feet together **Conditions:** EO, EC **Time between testing sessions:** 6 – 12 days	**Equipment:** AMTI OR6-3 force platform **Measures:** Root mean square distance: ML, AP Mean sway radius: ML, AP Sway path: ML, AP Area (triangle) Sway speed	Mean Pearson correlation *r* **EO:** Sway ML: 0.68 Sway AP: 0.53 Area: 0.85 Speed: 0.92	**EC:** Sway ML: 0.84 Sway AP: 0.83 Area: 0.96 Speed: 0.96

Levy et al. [72] T-RT	16 male, 31 female 75.8 ± 7.7 y	6 x 20 s (3 x EO and 3 x EC), 15 s rest Hands on hips, feet shoulder width apart, instructed to stay as still as possible **Conditions:** EO, EC **Time between sessions:** 3 days	**Equipment:** AMTI OR6-7 2000 force plate, mounted level to floor surface, BTrackS, 20 Hz, customized LabView **Measures:** Sway: AP, ML	ICC [2,1] (95% CI), SEM (cm), MDC 95% **EO, T-RT:** BTrackS: 0.83 (0.71, 0.89), 3.47, 9.6 **EC, T-RT:** BTrackS: 0.83 (0.71, 0.90), 7.0, 19.4	Pearson correlation *r* (95% CI) **EO, validity:** FP: 0.92 (0.88, 0.95) BTrackS: 0.95 (0.91, 0.97) **EC, validity:** FP: 0.95 (0.92, 0.97) BTrackS: 0.97 (0.94, 0.98)
Lin et al. [73] T-RT	Younger: 8 male, 8 female 20.3 ± 1.4, 21.5 ± 2.0 y 176.1 ± 4.6, 166.1 ± 5.2 cm 74.7 ± 12.1, 59.6 ± 5.1 kg Older: 8 male, 8 female 65.4 ± 3.7, 60.8 ± 6.4 y 175.5 ± 8.1, 160.2 ± 7.5 cm 88.9 ± 13.3, 66.2 ± 15.8 kg	3 x 75 s, 1 min rest Barefoot, feet together (feet traced), stand as still as possible, EC, arms at side, head facing straight ahead **Time between sessions:** Min. 2 days	**Equipment:** AMTI OR6-7-1000 force plate, 100 Hz **Measures:** Mean velocity: ML, AP Median power frequency: ML, AP Root mean square distance: ML, AP Sway area Hurts rescaled analysis: ML, AP Detrended fluctuation analysis: ML, AP	ICC (95% one-sided lower CI) **EC, Intra-session:** Younger: Velocity ML: 0.91 (0.81) Velocity AP: 0.86 (0.72) Sway area: 0.79 (0.60) Older: Velocity AP: 0.95 (0.90) Velocity ML: 0.95 (0.91) Sway area: 0.92 (0.84)	**EC, Inter-session:** Younger: Velocity ML: 0.79 (0.67) Velocity AP: 0.77 (0.65) Sway area: 0.72 (0.59) Older: Velocity ML: 0.91 (0.85) Velocity AP: 0.92 (0.87) Sway area: 0.90 (0.83)

Mani et al. [99] T-RT	36 male 40 ± 20 y 1.80 ± 0.06 m 79.25 ± 10.58 kg	3 x 30secs, no formal rest Shoes, feet in normal manner (feet traced), arms by their sides, EO, looking straight ahead (reference point 1.5m, eye level) **Conditions:** Bipedal, unipedal, limits of stability task, lifting task Counterbalanced **Time between tests:** 2-3 min between each testing period	**Equipment:** AMTI model BP2436, 10.5 Hz, Scilab 5.2.2 software **Measures:** Mean distance Root mean square distance Total excursion area Mean velocity Area 95 ellipse Area 95 circle Sway area Mean rotational frequency Composite and ML, AP for each measure	ICC [2,3] (95% CI) **EO, composite scores:** Distance: 0.84 (0.71, 0.91) Excursion: 0.95 (0.91, 0.97) Velocity: 0.95 (0.91, 0.97) Ellipse area: 0.84 (0.71, 0.91) Sway area: 0.86 (0.75, 0.92)	
Mattacola et al. [62] Rater	10 female, 2 male 24.7 ± 3.3 y 62.2 ± 7.5 kg 164.8 ± 7.1 cm 2 x 10 s	Focused on X marked on the wall in front of them, barefoot, knees slightly flexed (5 to 15˚), arms at sides, stand as still as possible **Conditions:** Double leg: static and dynamic, EO, EC Single leg: static, dominant and non-dominant leg, EO, EC Single leg: dynamic, dominant and non-dominant, EO **Time between raters:** 30 min	**Equipment:** Chattecx Dynamic Balance system, 2 raters **Measures:** Sway	ICC [2,1] , SEM (cm) **EO:** 0.06, 0.26	**EC:** 0.75, 0.06 cm

Moghadam et al. [64] T-RT	10 female, 6 male 69.6 ± 4.5 y 161.4 ± 6.22 cm 68.65 ± 9.57 kg	3 x 30 s, 1 min rest Stood quietly Barefoot, looking straight ahead, arms at sides, feet 50% hip-to-hip distance, blindfolded **Conditions:** EO, EC and foam EC (blindfold), dual task **Time between sessions:** 7 days	**Equipment:** Strain gauge & Bertec 4060-10 force platform 100Hz **Measures:** SD of amplitude: ML, AP SD of velocity: ML, AP Phase plane portrait: AP, ML, total Mean velocity Area 95 ellipse	ICC [2,3] (95% CI) **EO:** Velocity: 0.89 (0.58, 0.97) Area 95: 0.86 (0.44, 0.96)	**EC:** Velocity: 0.70 (0.00, 0.92) Area 95: 0.80 (0.18, 0.95)
Pinsault et al. [74] T-RT	5 male, 5 female 24.6 ± 2.5 y 175.1 ± 10.1 cm 68.9 ± 14.2 kg	10 x 30 s, 60 s rest Barefoot, EC, natural position (feet abducted at 30, heels separated by 3 cm and traced), arms hanging loosely by sides, stand as still as possible **Time between sessions:** 1 h	**Equipment:** Equi+ model PF01, 64hz **Measures:** Range Area Mean velocity Max velocity	ICC [2,1] (95% CI) **EC, 1 trial:** Area: 0.61 (0.08, 0.89) Velocity: 0.82 (0.57, 0.92) Max velocity: 0.79 (0.45, 0.94) **EC, 3 trials avg:** Area: 0.94 (0.81, 0.98) Velocity: 0.84 (0.55, 0.95) Max velocity: 0.80 (0.29, 0.94)	**EC, 10 trial avg:** Area: 0.91 (0.72, 0.95) Velocity: 0.89 (0.64, 0.97) Max velocity: 0.81 (0.29, 0.95)
Raymakers et al. T-RT	45 young, 38 older 21 - 45, 61 – 78 y	60 – 120 s Barefoot, feet parallel to a 4 cm T-shaped separator, EO looking at wall 150 cm in front **Conditions:** EO, cognitive, foam, EC **Time between sessions:** 7 days	**Equipment:** Kistler force platform, 10 Hz, Bioware software with customised program **Measures:** Sway range: AP, ML Mean displacement velocity Mean velocity	Standardised CV% **EO:** Range AP: 28% Range ML: 19% Velocity: 14% Area: 26%	

Riley et al.	7 male, 4 female 50.25 ± 22.63 y 1.71 ± 0.09 m 69.17 ± 11.29 kg 23.40 ± 2.09 kg/m2	2 x 7 s One foot on each force platform, feet in one of three stances **Conditions:** Wide base (heels 30 cm apart): EO Narrow base: EO, EC Semitandem (1 cm apart)	**Equipment:** Kistler force plates, SELSPOT II/TRACK acquisition system, 153 Hz **Measures:** Centre of gravity: ML, AP Centre of pressure: ML, AP	Pearson correlation *r* COG ML: 0.7459 COG AP: 0.5028 COP ML: 0.9134 COP AP: 0.7827	
Santos et al. [77] T-RT	12 male 26.9 ± 4.7 y 1.75 ± 0.07 m 74.9 ± 13.1 kg	8 x 60 s (4 x EO, 4 x EC) Barefoot, both feet parallel on both sides of a 5.1 cm T-shaped separator placed on the surface, arms hanging to their sides looking 2 m ahead **Conditions:** EO, EC counterbalanced **Time between sessions:** No later than 7 days	**Equipment:** AMTI BP900900 force platform, 100 Hz, In-house C++ system, MATLAB **Measures:** RMS distance Mean velocity COP range Mean frequency Median power frequency Sway area Area 95 ellipse	ICC **EO, one trial:** Velocity AP: 0.44 Velocity ML: 0.46 Range AP: 0.55 Range ML: 0.48 Sway: 0.55 Area 95: 0.40	**EC, one trial:** Velocity AP: 0.32 Velocity ML: 0.41 Range AP: 0.19 Range ML: 0.36 Sway: 0.38 Area 95: 0.43
Schmid et al. T-RT	4 male, 4 female 24 – 32 y	3 trials, 10 min rest Arms at sides, EO looking 3 m in front, feet hip width apart **Time between sessions:** 1 - 3 days	**Equipment:** Bertec 4060-08 force plate, 400 Hz, Step PC software **Measures:** Mean velocity Mean amplitude Sway area Mean power frequency Centroidal frequency	ICC **EO, 0.8Hz:** Velocity: 0.75 Sway area: 0.62	**EO, 10Hz:** Velocity: 0.71 Sway area: 0.55

Swanenburg et al. [79] T-RT Rater	18 female, 8 male 71 ± 6 y 69 ± 11 kg 166 ± 8 cm 34.4 ± 2 cm (hip width) 29.4 ± 3 cm (base of support width)	4 x 20 s, 20 s rest, 2 min in between tasks Barefoot (feet traced), double-leg stance, arms by their sides, looking straight ahead **Conditions:** EO, EC, no task, with task **Time between sessions:** 7 days	**Equipment:** AMTI Accusway, SWAYWIN software 50 Hz **Measures:** Max sway: ML, AP RMS: ML, AP Mean velocity Area 95	ICC [3,1] (95% CI) **EO, T-RT:** Max-ML: 0.75 (0.52, 0.88) Max-AP: 0.43 (0.06, 0.70) Velocity: 0.84 (0.68, 0.93) Area 95: 0.62 (0.32, 0.81) **EC, T-RT:** Max-ML: 0.83 (0.65, 0.92) Max-AP: 0.83 (0.65, 0.92) Velocity: 0.87 (0.74, 0.94) Area 95: 0.73 (0.49, 0.87)	ICC [2,1] **EO, rater:** Max-ML: 0.80 (0.60, 0.90) Max-AP: 0.56 (0.24, 0.72) Velocity: 0.81 (0.57, 0.87) Area 95: 0.65 (0.35, 0.83) **EC, rater:** Max-ML: 0.78 (0.57, 0.90) Max-AP: 0.84 (0.67, 0.92) Velocity: 0.89 (0.77, 0.95) Area 95: 0.76 (0.54, 0.89)
Takala et al.[80] T-RT	9 male, 9 female 38.7 ± 10.9 y 1.73 ± 0.10 m 69.5 ± 9.3 kg	3 (maximal) x 30 s Two-feet stance (4 cm apart), arms crossed, facing wall 150 cm in front, no shoes or thick socks **Conditions:** Two-feet: EO, EC One-foot: each foot, EO Stepping responses: both feet **Time between sessions:** 1 day and again 9 months	**Equipment:** Custom made force plate, 40 Hz **Measures:** Max sway: AP, ML Mean amplitude Sway velocity Mean sway frequency Sway area	ICC **EO, consecutive days:** Sway velocity: 0.64 Sway area: 0.57 **EC, consecutive days:** Sway velocity: 0.56 Sway area: 0.31	**EO, 9 months later:** Sway velocity: 0.86 Sway area: 0.64 **EC, 9 months later:** Sway velocity: 0.77 Sway area: 0.54

Study design	Population	Protocol and conditions	Equipment and measures	Outcome measures and results		
FSP						
Damsted et al. [29] Rater	17 female, 14 male Recreational runners 37 ± 9 y 176.5 ± 9.5 cm 73.3 ± 16 kg	5 consecutive steps, 2 raters Treadmill speed: 10.14 ± 1.47 km.h-1 **Foot-strike classification:** Heel-strike, heel-mid-foot, mid-foot, mid-fore, fore-foot **Time between sessions and ratings:** 7 days and Min. 14 days	**Equipment:** Exilim EX-F1, 300 Hz 86cm above the floor, 1.5m perpendicular to the treadmill, Run Xt Pro 600 Model D390 treadmill, own shoes, Kinovea 0.8.15 **Measures:** Intra-rater Inter-rater	Weighted Kappa **Intra-session, intra-rater: session 1, session 2:** Rater A : 0.88, 0.83 Rater B: 0.84, 0.88 **Intra-session, inter-rater:** A v B 1st session: 0.63, 0.60 A v B 2nd session: 0.55, 0.50	**Inter-session, 1st sessions:** Intra-rater: 0.66, 0.63 Inter-rater: 0.50, 0.53 **Inter-session, 2nd sessions:** Intra-rater: 0.69, 0.68 Inter-rater: 0.41, 0.43	
Pipkin et al. [51] Rater	8 male, 7 female 10 injured, 5 uninjured runners	3 blinded raters Treadmill speed: 3.17 ± 0.40m/s **Foot-strike classifications:** Heel strike, rear-foot, mid-foot, fore-foot **Time between sessions:** 7 – 10 days	**Equipment:** Casio EX-FH25 120Hz mounted on a portable tripod, Videopad video editor created still frame images, viewed on Quicktime **Measures:** Intra-rater Inter-rater	Average weighted Kappa (95% CI) **Intra rater:** 0.86 (0.36, 1.00) **Inter-rater:** 0.85 (0.75, 0.95)	**Number of selections:** Heel-strike 16 Rear-foot 15 Mid-foot 13 Fore-foot 1	
Santuz et al. [81] Rater	85 male, 60 female Inexperienced, recreational and competitive runners 175 ± 9 cm 69 ± 11 kg 22 ± 2 kg.m2 30 ± 9 y	8 raters Camera mounted on a tripod 29.5 cm high, set up 350 cm laterally to the left treadmill, angled perpendicular to the sagittal plane, 90 s in each condition **Foot-strike classification:** Rear-foot, mid-foot, fore-foot, combined Mid and fore (MFS) **Conditions:** preferred (shod 2.8 ± 0.4 m/s), faster speed (shod 3.5 ± 0.6 m/s), slower speed (shod 2.3 ± 0.3 m/s) and preferred speed (barefoot)	**Equipment:** Flare 4M180-CCL camera, 550 Hz, Simi Grab 2.1.1 software, FDM-THM-S pressure plate (120 Hz) integrated in a Mercury treadmill, WinFDM-T v2.5.1 software **Measures:** Inter-rater Inter-device	ICC (95% CI) **Preferred speed:** RS: 0.83 (0.77, 0.87) MS: 0.58 (0.50, 0.67) FS: 0.86 (0.82, 0.90) MFS: 0.83 (0.77, 0.87) **Faster speed:** RS: 0.86 (0.82, 0.90) MS: 0.51 (0.42, 0.60) FS: 0.65 (0.57, 0.72) MFS: 0.86 (0.82, 0.90)	**Slower:** RS: 0.89 (0.86, 0.92) MS: 0.64 (0.56, 0.72) FS: 0.73 (0.66, 0.79) MFS: 0.89 (0.86, 0.92) **Barefoot:** RS: 0.96 (0.94, 0.97) MS: 0.53 (0.44, 0.62) FS: 0.92 (0.89, 0.94) MFS: 0.96 (0.94, 0.97)	**Video v numerical:** RS: 0.93 (0.91, 0.94) MFS: 0.93 (0.91, 0.94)

Study design	Population	Protocol and conditions	Equipment and measures	Reliability results of selected results	
PF$_{isom}$					
Bemben et al. [82] T-RT	155 male, 12 age groups 22.2 ± 1.7 – 77.0 ± 1.4 y 76.0 ± 7.3 – 74.7 ± 2.8 kg 177.1 ± 6.1 – 175.9 ± 8.2 cm	3 x MVIC, 1 min rest, 5 min in between muscle groups Force testing table, semi-reclined, hands placed on hips and the left leg was extended, knees over edge Plantar flexion: the right knee at 180˚ and the ankle 90˚ **Conditions:** Finger flexors, thumb abductors, forearm extensors, dorsiflexors, plantar-flexors (randomized testing order) **Time between sessions:** 24 hr	**Equipment:** Daytronic model 9130 or model 300 **Measures:** Peak force (N) Time to peak force Peak force rate (60ms) Total impulse	Pearson correlation *r,* CV% **Peak force:** 20-24y: 0.90, 6.9% 25-29y: 0.77, 10.6% 30-34y: 0.62, 12.2% 35-39y: 0.84, 7.8% 40-44y: 0.80, 9.9% 45-49y: 0.93. 6.6% 50-54y: 0.90, 6.3% 55-59y: 0.77, 11.7% 60-64y: 0.87, 9.7% 65-69y: 0.66, 12.8% 70-74y: 0.62, 15.1% 75-79y: 0.37, 18.9%	 **Across all age groups:** Maximal Force: 0.99 Maximal Rate: 0.98 Total Impulse: 0.91
Clark et al. [83] T-RT	12 female, 5 male 20.9 ± 0.72 y 165.9 ± 2.4 cm 64.4 ± 2.4 kg	Min 4 x ~3-4 s MVIC, 1-2 min rest Seated, left keg, hip, knee, and ankle joints secured at 90˚ **Time between sessions:** 4 weeks	**Equipment:** Custom-modified Parabody 826, MLP-300-T force transducer, 625 Hz **Other:** EMG recordings, electrical stimulation, mechanical recording, MRI **Measures:** Peak force (N)	ICC [2,1] (95% CI), mean CV%, ratio LOA **Peak force:** 0.97 (0.92, 0.99), 4.19%, 15.15	
Clarke et al. [41] Rater	20 male, 18 female 21.8 ± 2.4 y	3 x 5 s MVC, 30 s rest, 3 m rest between testers Warm up, leg determined by coin toss, Position: prone lying on plinth, neutral ankle, hands by side, palms up **Conditions:** Constant order: Knee extension, hip extension, ankle plantar flexion **Time between ratings:** 7 days	**Equipment:** MicroFET3 HHD **Measures:** Peak force	ICC [3,1] (95% CI), SEM (N) **Intra-rater:** Rater 1: 0.56 (0.29, 0.74), 21.89 Rater 2: 0.88 (0.78, 0.94), 18.91	ICC [2,1] (95% CI) **Inter-rater:** Day 1:0.23 (0.03, 0.45) Day 2: 0.15 (0.04, 0.37)

Ford-Smith et al. [84] T-RT	17 female, 8 male 74.5 ± 4.5 y 3 x 3 s, approx. 30 s rest	Supine on treatment table with their ankles over the edge of the table, ankle passively paced in neutral position, force pad placed in contact with plantar surface **Conditions:** Flexor and extensor muscle groups for ankle, knee, and hip **Time between sessions:** 7 days	**Equipment:** AccuForce II Digital Force Gage attached to custom frame **Measures:** Peak force Composite force	ICC [3,1] (90% CI) **Peak force:** Right: 0.77 (0.59, 0.88) Left: 0.61 (0.36, 0.78) **Composite force:** 0.71 (0.50, 0.84)
Foure et al.[85] T-RT	8 male, 6 female 24.1 ± 2.2, 20.7 ± 1.6 y 179.6 ± 9.1, 166.2 ± 7.5 cm 74.3 ± 10.8, 58.0 ± 8.6 kg	2 MVC, 2 min rest Warm up: 3 min submaximal isometric plantar-flexion, seated, hip angle 70˚ flexion, right leg knee 0˚, left leg flexed in sitting position **Time between sessions:** 2 days	**Equipment:** Biodex dynamometer, Biodex research toolkit **Measures:** Peak torque	ICC [2,k] (CI), CV%, SEM (N.m) **Peak torque:** 0.91 (0.74, 0.97), 5.4%, 6.7
Joseph et al. [86] T-RT	5 male, 5 female 180 ± 4.9cm, 165.2 ± 7.1cm 97 ± 14.3kg, 67.8 ± 13.8kg 24 ± 1.4yrs, 23.6 ± 0.9yrs	3 s MVIC, ramp up and ramp down of 5 s each Seated, hip flexed, knee fully extended, ankle neutral, rest for 15 min then ultrasound measurements and MVC **Time between sessions:** 12 weeks	**Equipment:** Phillips HD11 ultrasound synchronized to a Biodex System 4 **Measures:** Peak torque	ICC, SEM (N.m) **Peak torque:** Intra-session: 0.99, 3.52 Intersession: 0.95, 7.77
Mattes et al. Rater	29 male 26.6 ± 4.3 y 181.4 ± 4.7 cm 79.4 ± 9.3 kg	3 x 5 s, 3 min rest Warm up – 10 min at 9km/h on a treadmill **Conditions:** Isometric strength then Isokinetic fatigue protocol (10 x 6 contractions, angular velocity 60˚/s, 10 s rest) **Time between sessions:** 3 – 7 days	**Equipment:** IsoMed 2000 dynamometer, 20 Hz **Measures:** Intra-rater Maximum torque	ICC [3,1] (95% CI), SEM (N.m) **Maximum torque:** 0.98 (0.96, 0.99), 4.0

Moraux et al. [87] T-RT	76 subjects for re-test	2 x 2-4 s, 30 s rest between contractions Seated, right angle at hip, knee and foot, foot flat on the dynamometer, pull against the strap **Conditions:** Dorsiflexion and plantar-flexion: L, R **Time between sessions:** At least 1 hr up to 30 days	**Equipment:** Home-made dynamometer **Measures:** Maximal torque	ICC [2,1], SEM (N.m), LOA **Maximal torque, Plantar-flexion:** 0.88, 11.0, 30.6
Sleivert et al. [89] T-RT	20 male, 3 female 24.7 ± 3.6 y 75.8 ± 9.6 kg 184.1 ± 6.3 cm Sum of 8 skinfolds 80.0 ± 32.9 mm	3 x 3 s at each speed: 0, 1.05, 2.10. 3.14 and 4.19rad/s-1 Upper body immbolized with straps, supine position, knee and ankle set at 100˚ **Time between sessions:** 48 hrs	**Equipment:** Cybex UBXT dynamometer, ATCODAS signal processing software, 2000 Hz **Other:** Nerve conduction velocity, EMG **Measures:** Peak torque Peak RTD % of peak torque at peak RTD	ICC, SEM (N.m) Peak torque: 0.72, 15 SEM (Nm.s ^{1}) **RTD:** Mean: 0.63, 54 Peak: 0.13, 278 % peak torque at peak RTD: 0.02, 8
Spink et al. [42] Rater	17 male, 19 female 23.2 ± 4.3 y 172.7 ± 9.1 cm 67.2 ± 11.3 kg 22.4 ± 2.6 BMI 17 male, 19 female 77.1 ± 5.7 y 164.4 ± 10.3 cm 73.8 ± 14.0 kg 27.2 ± 3.7 BMI	3 x 3-5 s contractions Supine position with hips and knees extended and the lower limb stabilized proximal to the ankle joint, dynamometer placed on the plantar surface just proximal to the metatarsal heads **Conditions:** Ankle: dorsiflexion, plantar-flexion, inversion, eversion, lesser toe plantar-flexion, hallux plantar-flexion **Time between sessions:** 7 days	**Equipment:** Citec hand-held dynamometer **Measures:** Mean force	ICC [3,1] (95% CI), CV%, MDC (N) **Intra-rater:** Rater 1: 0.89 (0.83, 0.93), 7.9%, 52.0 Rater 2: 0.84 (0.76, 0.90), 14.1%, 85.8 **Inter-rater:** Session 1: 0.80 (0.70, 0.87), 13.6%,77.9 Session 2: 0.82 (0.72, 0.88), 12.8%, 72.1

Topp et al. T-RT	9 male, 13 female 72.8 ± 5.1 y	3 MVIC, 30 s rest Seated, both knees fully extended, no back support, hands on knees, hip flexion approx. 90˚, latereal malleous aligned with edge of platform **Conditions:** Isometric: dorsiflexion, plantar-flexion Isokinetic concentric and eccentric: dorsiflexion, plantar-flexion **Time between sessions:** 7 days	**Equipment:** Microfet HHD, 2-inch diameter concave pressure distributing plate **Measures:** Peak torque	Pearson correlation *r* **Isometric, peak torque, intra-session:** Session 1: 0.93 Session 2: 0.92	 **TRT:** 0.76