GAIT RETRAINING FOR REDUCING BIOMECHANICAL INJURY RISK FACTORS IN NOVICE RECREATIONAL RUNNERS

by

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Abstract

Introduction: The etiology of running-related injuries is multifactorial, but it is accepted that biomechanical factors play a role. This thesis examined the influence of peak braking force on running-related injury risk and the effectiveness of a gait retraining program using real-time biofeedback to reduce this parameter in high-risk individuals.

Methods: Healthy novice female recreational runners were recruited from the local running community. The studies in Chapters 2 and 3 were run in parallel, while the study described in Chapter 4 took place following their completion. Kinetic risk factors of running-related injury were examined using a prospective longitudinal cohort design and Cox proportional hazard models with competing risks were fit for each kinetic variable independently (Chapter 2). Baseline data were then analyzed to determine the kinematic correlates of kinetic risk factors using stepwise multiple linear regression to evaluate the amount of variance in each kinetic outcome explained by speed, foot strike angle, and kinematic variables associated with overstriding (Chapter 3). Finally, a similar but separate sample of female recreational runners considered to be at higher-risk of developing injury (peak braking force>0.27 BW) were enrolled in an eight-session gait retraining program using real-time biofeedback of the anterior-posterior (braking) ground reaction force (Chapter 4).

Results: Peak braking force was associated with a five to eight-fold increased risk of running-related injury. Our findings suggest that the use of peak braking force may be a more effective target for gait retraining than vertical loading rate. Regression analysis of kinematic variables revealed that shortening step length and transitioning away from a rearfoot strike pattern are appropriate strategies to reduce peak braking force. An eight-session gait retraining program significantly reduced peak braking force, as well as vertical loading rates associated with

running-related injury. This was achieved predominantly through a combination of increased step frequency and decreased step length.

Conclusions: This dissertation provides new understanding of the role of kinetic risk factors—specifically peak braking force—in the development of running-related injury. Furthermore, it provides the structure for a larger randomized controlled trial to assess a gait retraining intervention to reduce peak braking force and running-related injury risk.

Lay Summary

Running has numerous health benefits, but also carries a high risk of musculoskeletal injury. Risk factors for running-related injury include training error, anatomical abnormality, and biomechanical dysfunction. Among biomechanical risk factors, parameters related to vertical loading have been well studied. We sought to investigate the anterior-posterior (braking) force as it relates to the development of running-related injury. We found that female recreational runners who had higher braking forces were injured at five to eight times the rate of runners with medium or lower braking forces, and that this was a better measure than vertical loading rate. Associated with these higher braking forces were a longer step length and a more rearfoot landing pattern. When runners with high braking forces were retrained using real-time biofeedback, they were able to lower their braking force by decreasing their step length and increasing their step frequency.

Preface

The work in this dissertation was conceived, conducted, and written by Christopher Napier. Research described in this dissertation was approved by the University of British Columbia's Clinical Research Ethics Board: H13-02973 and H16-00413.

Chapters 1 and 5 were written by Christopher Napier. Drs. Michael Hunt, Christopher MacLean, and Jack Taunton assisted in editing these chapters.

Chapter 2 is based on work conducted by Christopher Napier, Drs. Michael Hunt, Christopher MacLean, and Jack Taunton. Christopher Napier was responsible for the study design, data collection, analyses and interpretation, and writing and revising the manuscript. Dr. Hunt assisted in study design, analysis, interpretation, and editing the manuscript. Drs. MacLean and Taunton assisted in study design, interpretation, and editing the manuscript. Jessica Maurer assisted in editing the manuscript.

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Finally, my family. Kate Shannon, thank you for your endless support and for the many hours of solo parenting over the course of my degree. Bella and Roewan, you have kept me

focused on what is truly important in life and I thank you for your unconditional love. And to my mother and late father, who always inspired me to ask why. Thank you.

Dedication

To my mother and late father who inspired me to chase my dreams and always ask why.

To Bella and Roewan, for keeping me focused on what is truly important in life.

And to Kate, who has supported me throughout this journey and has taken on far more than her share to make this possible.

Chapter 1: Introduction

1.1 Running-related injury

Regular physical activity is known to produce significant health benefits, yet recent data suggest that only 15% of Canadian adults are meeting the recommended guidelines (1). Running has benefits in the prevention of obesity, hypertension, type 2 diabetes, osteoarthritis, respiratory disease, cancer, and disability (2). Even in low doses, running is associated with a substantial reduction in cardiovascular and all-cause mortality (2). Within the context of an overall downward trend in physical activity in the general population, long distance running appears to be experiencing a boom in participation (3). Most major cities in North America now have their own marathon and multiple recreational running events. With an increase in participation, these events are attracting more novice runners. Importantly, novice runners are the most at risk of developing a running-related injury according to several studies and therefore may benefit the most from preventative interventions (4-7). Studies have suggested that the primary reason for novice runners to participate in a running program is to improve health and fitness, while for intermediate runners it is to improve personal performance (5). Apart from its beneficial health effects, the repetitive nature of running in combination with the high cumulative loads exerted on the body also puts participants at risk of developing an overuse injury. In fact, one of the primary barriers to maintaining the recommended level of physical activity is musculoskeletal injury. The incidence of running-related injury varies from 19% to 85% (4,5,8-10) and this rate has not decreased appreciably in the last 30 years (10). Such high injury rates impact quality of life, health, and productivity. They also discourage new runners from continuing in the sport as a significant portion of those injured do not return to running (4,8).

1.2 Running-related injury definition

The literature has been inconsistent in its definition of running-related injury, despite attempts at consensus. As such, rates may be underestimated or overestimated depending on the definition used for injury. These definitions have been as strict as "an injury that cause[s] the runner to stop running for at least seven days" (yielding an incidence of 24%) (9) and as general as "any physical complaint developed in relation with running activities and causing restriction in running distance, speed, duration, and frequency" (yielding an incidence of 84.9%) (8). Several studies have been carried out using a Vancouver-based running population and defining a running-related injury as a running-related event that causes three consecutive missed run workouts. These studies have consistently yielded an injury rate of between 23-32% (5,11,12). A recent systematic review found that two main domains needed to be met to define a running-related injury: 1) the presence of a physical complaint and 2) the need for a period of interruption (13). To address the absence of a standardized definition of a running-related injury, a panel of experts recently proposed a consensus definition, defining it as "running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on, or stoppage of, running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional (14)."

1.3 Etiology of running-related injuries

1.3.1 Training error as a risk factor of running-related injury

It could be said that all overuse running-related injuries are a result of training errors, since to sustain an overuse injury one has to err by exceeding the limits in such a way that the repair process cannot keep pace with the stresses placed upon that structure. Injury occurs when the rate of application exceeds the rate of adaptation of the tissues. Training errors that have most often been identified as risk factors include excessive volume or intensity, or rapid changes in these variables (6,15). Other training-related variables that have been associated with development of running-related injuries are running surface (7) and footwear (5). Outside of the running literature, a model described by Gabbett purports that athletes accustomed to high training loads have fewer injuries than athletes training at lower workloads, but this has yet to be applied to the sport of distance running (16). Taking this model and applying it to running, it makes sense that gradual increases and sustained running volume and intensity will have a protective effect against injury. Furthermore, there is evidence that under-training may also increase injury risk in a number of sports (16). This may be one explanation for why novice runners are at an increased risk of running-related injury when compared to experienced runners (4-7). Regardless of training error, differences in individual thresholds exist between runners and between anatomical structures. It is therefore logical to assume that a combination of anatomical and biomechanical factors also contribute to injury risk.

1.3.2 Anatomical risk factors of running-related injury

The role of anatomical risk factors in the development of running-related injury is less clear. There is lack of agreement in the literature over many proposed anatomical risk factors.

This may be explained by the theory that as long as adequate time is given for tissues to adapt to training loads, many anatomical abnormalities may be accommodated (17). There is limited evidence that leg length discrepancy and greater knee varus alignment are associated with running-related injury (10). Higher body mass index has also been associated with injury in female runners (4). Arch height has been implicated as a risk factor of running-related injury in a number of studies, but other studies have concluded that it is not a risk factor (15). There is also conflicting evidence regarding age, with greater age generally resulting in increased injury risk (10). One risk factor that has been frequently associated with running-related injury is previous injury (5,7,10). For this reason, most studies using 'healthy' populations require that participants have been free from injury for at least three to six months prior to study commencement. Interestingly, one prospective study did compare runners who had never been injured—a rare group—to those who had been medically diagnosed with a running-related injury and found a difference between groups that was not apparent when simply comparing injured versus uninjured (18).

1.3.2.1 Sex differences in running-related injury

There is limited evidence for gender as a determinant of running-related injury, with females being at greater risk (10). More importantly, differences in type and mechanism of running-related injury have been reported between males and females (19-21). A greater number of females entering running clinics also tend to be novice runners (5). Given the difference in injury mechanisms and that lack of running experience is a significant risk factor for running-related injury, studying the running population by gender is important to avoid confounding variables.

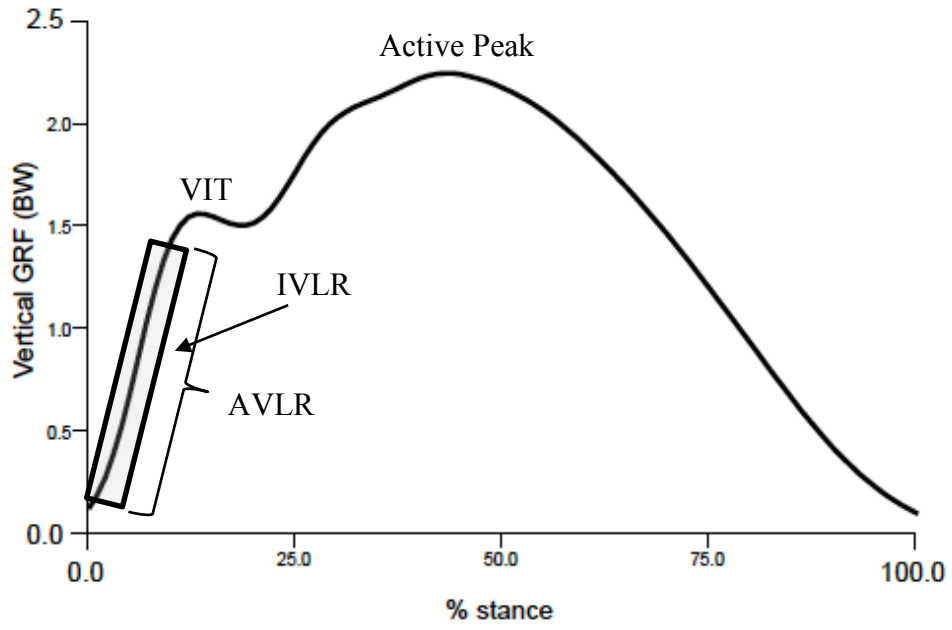
1.3.3 Biomechanical risk factors of running-related injury

Errors in training, anatomical factors, or faulty running technique may increase the biomechanical stresses placed on the body. Recent research has suggested that changing biomechanics may have a protective effect on running-related injuries, regardless of training or anatomy (22). Therefore, investigations into biomechanical risk factors and gait retraining strategies have significant clinical importance. Proposed biomechanical risk factors include kinetic, kinematic, and spatiotemporal parameters (5,12,23). Few biomechanical variables, however, have been supported by strong empirical evidence. Of these variables, impact loading (the sudden force applied to the skeleton at initial contact) has been the most studied.

1.3.3.1 Kinetic risk factors of running-related injury

The ground reaction force has been an important measure in many studies on the biomechanics of running, and is typically used to quantify the degree of impact loading on the lower extremity (24). The plot of the vertical ground reaction force-time curve of a rearfoot striker characteristically includes two force peaks—the vertical impact transient and the vertical active peak (Figure 1.1a). A non-rearfoot striker typically displays a muted or absent vertical impact transient. The average vertical loading rate has previously been defined as the average of the slope in the region between 20% and 80% of the vertical impact transient in the vertical ground reaction force-time curve and is an indication of how fast the vertical ground reaction force rises to its first peak, whereas the instantaneous (or peak) vertical loading rate measures the maximum loading rate within this time frame (25). The anterior-posterior ground reaction force curve also displays two main peaks—a posterior (braking) peak in the first half and an anterior (propulsive) peak in the second half of stance (Figure 1.1b).

(a)



(b)

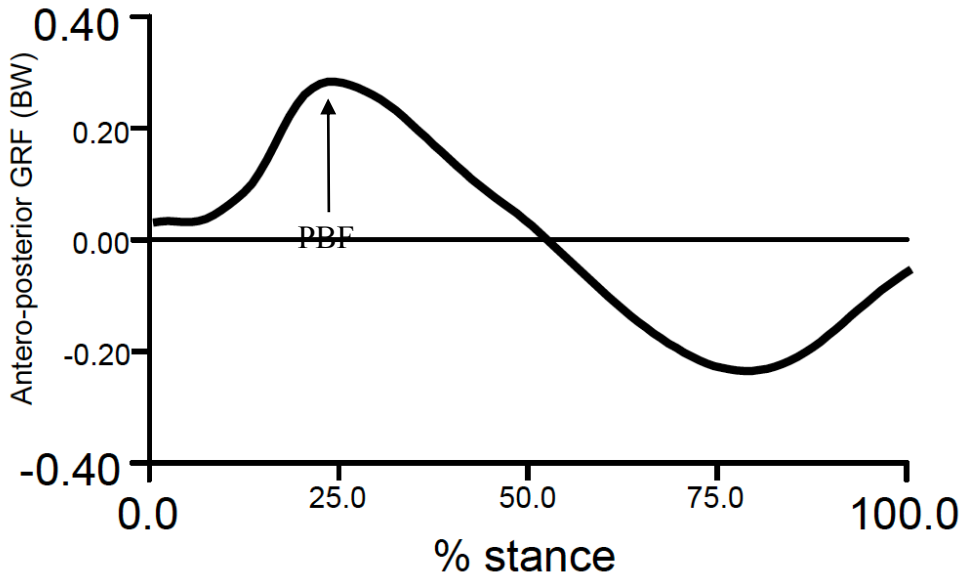


Figure 1.1 Vertical (a) and antero-posterior (b) GRF curves.
Horizontal GRF curve is shown inverted with braking force shown as positive for purpose of comparison. GRF, Ground reaction force; BW, Body weights; VIT, Vertical impact transient; IVLR, Instantaneous vertical loading rate; AVLR, Average vertical loading rate; PBF, Peak braking force.

Aside from a few recent prospective studies (18,20,26), the research linking impact loading and lower extremity overuse injuries has been largely based on retrospective and cross-sectional studies (27-30). Higher average vertical loading rate (24,28), instantaneous vertical loading rate (27-29), and vertical impact transient (27,28) have all been associated with increased running-related injury rates in retrospective analyses. A study by Hreljac et al (27) found that runners with a history of at least one previous overuse injury had a significantly greater magnitude and rate of instantaneous vertical loading than runners who were injury free, which suggests a link between vertical ground reaction forces and injuries. A systematic review by Zadpoor et al (24) found that while a greater average vertical loading rate was significantly associated with populations who had suffered a tibial stress fracture versus control populations, the overall magnitude of the vertical ground reaction force was not. The authors hypothesized that this may be due to individual differences in the geometry or strength of bones, or because ground reaction force magnitude does not completely represent the loading of bones.

Prospective studies and a recent systematic review have produced conflicting results, with vertical loading rate—whether measured as average or instantaneous—illustrating the closest association with running-related injury (18,20,26,31). Davis et al (18) recently reported higher average vertical loading rate across all injuries when comparing medically-diagnosed injured female runners to runners who had never suffered a running-related injury. However, when simply comparing injured to uninjured runners, there was no difference in average or instantaneous vertical loading rates, or vertical impact transient magnitude. Bredeweg et al (20) also reported higher instantaneous vertical loading rates among prospectively injured males, but the same did not hold true for female runners. Furthermore, when a Cox regression analysis was

performed taking into account exposure time, there was no association between instantaneous vertical loading rate and running-related injury among the male runners. Similarly, Kuhman et al (26) did not find a difference in instantaneous vertical loading rate between prospectively injured and uninjured runners, though this study had a small sample size (n=19) and included both males and females in the analysis.

The conflicting results of the aforementioned studies may be explained by the fact that different injuries likely have different biomechanical etiologies. In support of this argument, a systematic review by van der Worp et al (31) indicated that average vertical loading rate was higher in runners with a history of stress fracture, but not in those with tendinopathy, anterior knee pain, or iliotibial band syndrome. Therefore, the make-up of injuries in each study could influence the significance of the outcomes. Another explanation for this disagreement could be the populations studied, with competitive runners likely being able to withstand higher loading rates than novice/recreational runners (32). Interestingly, a large randomized controlled trial investigating the effectiveness of a two-week, eight-session gait retraining program aimed at reducing vertical loading in recreational runners reported a significant reduction in average vertical loading rate after the two-week intervention and a 62% reduction in running-related injury in the intervention group at 12-month follow-up (22). The results of this study demonstrate the influence that a reduction in vertical loading rate might have on the development of running-related injury.

The anterior-posterior ground reaction force has been less studied. The braking force (Figure 1.1b; the posteriorly directed component of the ground reaction force vector from initial contact to midstance) has been examined in some studies. However, most of these investigations have primarily reported the metabolic and performance costs of greater braking forces during

running (33-35). Two studies have investigated biomechanical risk factors for tibial stress fractures retrospectively, but did not find a relationship between braking forces and injury rates (28,36). In contrast, Grimston et al (37) reported higher peak braking forces in females with a history of tibial stress fracture. In yet another contrast, Messier et al (38) reported that peak braking force was actually lower in runners with patellofemoral pain than in healthy controls. In a follow-up study, the authors reported that a low peak braking force was also associated with runners with iliotibial band syndrome (39). The results of these latter two studies might be explained by a reluctance to braking in a retrospective population that has already sustained an injury rather than implying causation. Indeed, a higher peak braking force fits with injury prediction theories. It is known that bones do not withstand shear (horizontal) forces as well as they withstand compressive (vertical) forces, despite the magnitudes being several times greater for the latter (40,41). Although shear forces are relatively small, they can become substantial in long bones (such as the tibia or femur) that are subjected to torsion (41). Torsional loading causes shear stresses along and transverse to the long axis of the bone, which has been suggested to lead to the development of stress fractures (41).

The same may be true for other soft tissue structures which in the lower extremities contain primarily axially-oriented fibres. These fibres are built to withstand vertical more than horizontal stresses and strains. For instance, the posterior and anterior long muscles of the femur and tibia (along with their tendon components) are designed to eccentrically control their rate of lengthening to attenuate the vertical propagation of forces from the ground up to the knee and hip. Joint stiffness is also mediated by the eccentric contraction of these longitudinal muscles. Shear loads, on the other hand, may be more difficult for muscle forces to attenuate given that most muscles are oriented in a way to either produce or absorb forces in an axial direction. As a

result, shear forces are regulated via co-contraction of opposing muscle groups (such as the hamstrings and quadriceps at the knee) resulting in compression of joints and indirect control of shear forces. This indirect control of forces may be more demanding on the soft tissues of the lower extremities and may place more stress on these muscles, resulting in breakdown over repeated cycles.

Shear forces applied to the foot and lower leg may also increase the risk of certain injuries to these regions (42). Specifically, the tibia (37) and metatarsals (43) have been suggested to be less able to withstand horizontal than vertical loads. Increased shear forces may also play a role in the development of some soft tissue injuries such medial stress syndrome (44).

To date, there have been no prospective studies that have investigated the relationship between braking force and running-related injury.

1.3.3.2 Kinematic and spatiotemporal risk factors of running-related injury

Multiple kinematic and spatiotemporal variables have been proposed to contribute to the development of running-related injury. These include peak sagittal plane angles at the ankle, knee, and hip (23,28,45); peak rearfoot eversion/inversion (28,45,46); peak sagittal and frontal plane angles of the pelvis (47); angle of the shank at initial contact (48); foot strike angle (49); horizontal distance from heel to centre of mass at initial contact (48); vertical excursion of the centre of mass (48); step frequency, step length, and ground contact time (48,50). Joint angles in the lower extremity at the point of initial contact are thought to be related to impact loading, with greater flexion of ankle, knee, and hip joints allowing the skeleton to better absorb impact and distribute the stress amongst soft tissues (51). Shock attenuation—the process of absorbing and reducing the amplitude of energy from impact—has also been associated with kinematic and spatiotemporal

variables. Shock attenuation is thought to play a role in the development of injury and is considered to be dependent on the spatial orientation (joint angles) of the lower extremity segments at initial contact as well as step length and frequency (51,52).

Some studies have looked at the effect of foot strike positioning on impact loading. It has been reported that rearfoot strikers suffer approximately twice the rate of overuse injuries as forefoot strikers (49). A rearfoot strike pattern results in a more distinct impact peak, which may be eliminated or significantly reduced with the adoption of a midfoot or forefoot strike landing pattern (53). Interestingly, while vertical ground reaction force magnitudes may be decreased, Boyer et al (54) demonstrated that forefoot strike runners had peak braking forces 450% greater than in rearfoot strike runners. It is reported that up to three-quarters of runners make initial contact with the ground using a rearfoot strike pattern (55). Numerous studies have demonstrated reductions in impact loading, step length, and ground contact time as well as an increase in step frequency when adopting a forefoot versus rearfoot strike (56-59). Some studies have also shown that a reduction in step length—with a corresponding increase in step frequency—can change a rearfoot striker into a forefoot striker (48,50). By manipulating foot strike pattern, it has been suggested that injury risk may be reduced (53), but it is unknown whether it is another kinematic or spatiotemporal correlate of impact loading (such as a change in angle at the knee or shank at initial contact, or a shortening of the step length) that is ultimately responsible.

Step frequency and step length are innately linked. An increase in one will produce a decrease in the other, all else being equal. However, the residual effects on other spatiotemporal parameters of running gait are less clear. Generally, a greater step length has been associated with novice runners and potentially a higher incidence of injury (50). This may, in part, be due to the increased vertical ground reaction force and external hip flexion and knee extension

moments produced with a greater step length (60). Further, Mercer et al (52) reported that increases in step length reduced shock attenuation in runners, independent of step frequency. The authors posited that shock attenuation, by way of impact magnitude, was decreased at longer step lengths due to alterations in lower extremity posture and compliance at initial contact.

Lieberman et al (61) noted that increases in step length can be achieved either by a longer flight phase or by landing with a more extended lower extremity with a greater heel to centre of mass distance at initial contact (colloquially referred to as "overstriding"). Furthermore, the unique combination of hip and knee flexion at initial contact can affect the appearance of this overstride, with greater knee extension and hip flexion—resulting in an increase in shank angle and horizontal distance from heel to centre of mass—producing greater braking force and impact peak magnitude (61). Clinically, angle of the shank at initial contact is often viewed as an indication of overstriding, but this measurement has never been validated in the lab.

The posture of the lower extremity at initial contact and during the loading phase has been reported to influence the magnitude and rate of loading (48,61,62). In a step rate intervention, Heiderscheit et al (48) found that decreased step frequency—and a corresponding greater step length—resulted in less knee flexion and greater hip flexion at initial contact. This produced a higher braking and active peak. The increased step length was accompanied by an increase in the horizontal distance between the heel and centre of mass at initial contact. Alternatively, with an increase in step frequency of 5-10%, the knee was more flexed and the initial contact occurred more underneath the body's centre of mass, resulting in less overstriding and decreased load experienced by the lower extremity joints. In addition, running with a greater step frequency reduced peak hip adduction (48), which has been linked to anterior knee pain and iliotibial band syndrome in running (23). Another study suggested that a 10% reduction in step

length and equivalent increase in step frequency reduces the risk of developing a tibial stress fracture (50).

Few studies have specifically examined the relationship of these kinematic or spatiotemporal variables with kinetic risk factors, but the importance of establishing a clear link between these correlates of kinetic variables and risk of developing a running-related injury cannot be understated. Many of these variables are modifiable through gait retraining and knowing the independent relationships between each variable and kinetic risk factors might aid clinicians and researchers in developing a gait retraining program specific to the individual.

1.3.4 Effect of running velocity on biomechanical outcomes

Running speed directly influences kinetic parameters via increased force production to propel the centre of mass vertically and horizontally forward. Therefore, it must be accounted for when comparing biomechanical outcomes between individuals (28,63). One solution is to constrain the speed for analysis, but runners may alter their running style when forced to run at a fixed speed rather than their preferred (28,63). Importantly, based on our previous experience, we have found that novice runners in particular have difficulty determining their preferred pace (64). Alternatively, choosing to fix the intensity (based on Borg's Rating of Perceived Exertion Scale), rather than fixing the speed or asking the participant to identify a self-selected pace, allows for standardization of intensity across participants while still maintaining individual preferred form (65). In a recent analysis of rating of perceived exertion and maximal running time, it was found that a beginning rating of perceived exertion of 13 ("Somewhat hard" or 70% effort) corresponded to a running time of 34 minutes until exhaustion (or a rating of perceived

exertion of 17—"Very Hard" or 90% effort) in a healthy novice running population (unpublished data).

1.4 Running gait retraining

Recently, running gait retraining has become a popular mode of treatment for running injuries, with promising results (22,66). Gait retraining has been suggested by some experts to be the most effective method to reduce loading parameters (66-68), with several studies showing the ability to lower vertical loading rates through a gait retraining intervention with real-time biofeedback of vertical ground reaction force or tibial acceleration (22,69,70). In fact, a systematic review by our research group found that real-time kinetic or kinematic feedback was the most effective strategy for reducing vertical loading (71). This form of feedback may be effective because it allows the runner to develop their own movement strategy, rather than adhering to specific kinematic or spatiotemporal cues. Interventions that focus on such cues (increase cadence or change to a forefoot strike, for instance) may not be appropriate for all runners (high cadence or habitual forefoot strike runners, for instance) (68), so allowing the runner to develop their own strategy may be a better alternative than a 'one size fits all' approach (66).

There have been several examples of gait retraining programs that have proven effective. Many of these studies have involved injured populations (53,72-74), but some have investigated the effects in healthy runners (22,75). Perhaps the most compelling of these studies to date is Chan et al's (22) recent large randomized controlled trial investigating the effectiveness of a gait retraining program aimed at reducing vertical loading rates. The intervention consisted of a two-week real-time visual feedback gait retraining protocol in 166 runners. At 12-month follow-up,

the authors reported a reduction of 62% in running-related injury risk in the intervention group. This finding suggests that gait retraining programs should be considered an attractive option for reducing running-related injury risk among healthy individuals. Given the substantial impact that a gait retraining intervention may have on injury risk, it is important to test protocols to determine their effectiveness at achieving their targeted outcome. In the case of kinetic feedback protocols, it is also important to determine the kinematic changes that are produced in order to guide clinical application.

While many of the most effective interventions have relied on lab-based feedback of kinetic metrics, this may not be feasible in a clinical setting due to constraints on equipment, costs, and analytic methods. Fortunately, many kinematic variables can be measured and modified in a clinical setting simply by using 2D video (76,77). There are also at least two examples of gait retraining programs that have used clinician cueing and have been successful at reducing vertical loading parameters (75,78). Debate in the literature and among clinicians exists as to how runners should be instructed to achieve a reduction in ground reaction force variables associated with injury, with experts disagreeing on the importance of reducing overstride versus changing foot strike pattern (66). While the reduction of an overstride is considered by many to be one of the most beneficial gait retraining strategies—because of the presumed reduction of braking and vertical ground reaction force—evidence to support the relationship between overstriding and running-related injury is lacking (66). Conversion from a rearfoot to a forefoot strike pattern, on the other hand, has shown a clear reduction in vertical loading rates (53,79). Therefore, knowledge of specific kinematic variables that relate to overstriding and lower extremity posture at initial contact could inform clinic-based gait retraining programs aimed at reducing kinetic risk factors of running-related injury.

Identifying the independent contributions of kinematic and spatiotemporal parameters to impact loading is important because this information will provide understanding of the beneficial consequences of gait retraining in runners. Previous work has demonstrated some relationship between these aspects of gait when manipulated in a laboratory setting (48,53,57,80). For instance, an increased step frequency produces a reduction in vertical ground reaction force (48), and a change to a forefoot strike pattern decreases the average vertical loading rate and instantaneous vertical loading rate (53,79). Two papers have reviewed the direct influence of a modifiable variable (step frequency/length) on running mechanics, finding an inverse relationship between peak vertical ground reaction force and step frequency (48,81). A number of other strategies have been suggested, including modification of foot strike pattern (with a forefoot strike pattern reducing impact loading, step length, and ground contact time) (53,82) and sagittal hip, knee, and ankle joint angles at initial contact (with greater flexion being associated with decreased vertical ground reaction force) (57,80). There is a complex relationship between these kinetic, kinematic, and spatiotemporal aspects of running, with intentional manipulation of some variables producing unintended consequences in others.

1.4.1 Real-time biofeedback

Numerous studies have shown that individuals can be trained to modify aspects of walking and running (22,25,48,53,57,67,74,83,84). Moreover, gait retraining using real-time biofeedback has been shown to decrease pain and increase function when treating overuse injuries in runners (53,57,67,74). However, since it is unclear what variables independently contribute to the recovery from these injuries and whether these variables can be manipulated prospectively to reduce the risk of injury, optimal prevention and treatment of running-related

injury remains unknown. The above studies all included some form of feedback to the participants, which helped them modify their technique. The feedback methods included verbal instructions and real-time visual (22,25,48,74,83,84) or auditory information (53,57). Other studies used verbal instructions and an extensive training program (57,80). Many of these studies have used overlapping instructions and feedback which make it difficult to infer which factors had a causative effect on changing gait mechanics, muscle activation patterns, and ground reaction forces. Other studies have used feedback that is difficult to reproduce outside of a lab or clinic environment (22,25). Simple cues that produce a specific and intended kinematic or spatiotemporal modification are necessary.

1.4.2 Motor learning principles

Motor learning principles play an important role in any gait retraining intervention and must be taken into account when designing a protocol (68). Participants who receive intermittent feedback have been shown to perform better in the long-term than participants who receive continuous immediate feedback (85,86). Removing the feedback is beneficial to motor skill learning because the participants must rely on internal cues for performing correct motor patterns (68,87). In addition, clinical feasibility should also be taken into consideration so that the results may be generalizable to this context (88).

1.4.3 Length of training program

There has been recent debate around the optimal design of a gait retraining program with recommendations to standardize length and number of sessions in protocols (68). Arendse et al (80) reported that 7.5 hours of training over 5 consecutive days was required to learn forefoot

landing, while Dallam et al (89) reported a 1-hour session for 12 weeks was necessary. Diebal et al (57) showed forefoot landing could be trained in 6 weeks, with training sessions 3 times per week for 45 minutes. An 8-session faded-feedback approach was used by Barrios et al (83) to retrain walkers. This design produced changes in lower extremity biomechanical variables immediately post-intervention as well as at 1-month follow-up. Several running gait retraining interventions have also followed this structured feedback approach (72-74) and it has been favoured by one recent editorial (68).

1.4.4 Future directions

Some researchers have suggested that further studies should investigate the effect of gait retraining on injury prevention in runners (57,80). However, it is plausible that intentionally changing running dynamics to reduce injury risk may have unintended consequences such as increasing the chance of another kind of injury if other kinematic or spatiotemporal variables are adversely impacted (60,80). For this reason, the safety of such programs needs to be evaluated. Knowledge of the independent contributions of identified kinematic and spatiotemporal risk factors to impact loading and injury incidence will allow for targeted modification of these variables so that the risk of negative consequences is limited.

1.5 Thesis outline

This project was designed as three related studies. All studies received ethical approval from the University of British Columbia Clinical Research Ethics Board and informed, written consent was gained from all participants. The studies outlined in Chapters 2 and 3 were run in parallel, while the study described in Chapter 4 took place following their completion. The first

study (Chapter 2) was a prospective longitudinal cohort design aimed at determining the predictive capacity of kinetic risk factors on the incidence of running-related injury. The second study (Chapter 3) was a cross-sectional design—using baseline data alone from the prospective study comprising Chapter 2—to determine the kinematic and spatiotemporal correlates of kinetic risk factors of running-related injury. The third and final study was an interventional, repeated measures design to determine whether a gait retraining program is able to change kinetic risk factors of running-related injury in a recreational running population. Biomechanical analyses for all three studies were completed at the Fortius Institute's Biomechanics Laboratory with data collected on an instrumented treadmill. Participants in the studies outlined in Chapters 2 and 4 also underwent a 15-week half-marathon training program in the community (see section 1.6.3 and Appendix A for details).

1.5.1 Objectives and hypotheses

1.5.1.1 Chapter 2

Objective: The purpose of this study was to determine the predictive capacity of specific kinetic variables on running-related injury risk.

Hypothesis: Our primary hypothesis was that average vertical loading rate would be the best predictor of running-related injury and that it would yield the highest injury hazard ratio. Our secondary hypothesis was that peak braking force would also be predictive of running-related injury.

1.5.1.2 Chapter 3

Objective: The purpose of this study was to determine if kinetic risk factors of running-

related injury could be estimated from specific kinematic variables related to overstriding.

Hypothesis: We hypothesized greater step length, landing with a more flexed hip, a greater horizontal distance between heel and centre of mass, and greater shank angle at initial contact would significantly contribute to the variance in all kinetic outcomes. We also hypothesized that foot strike angle would be a significant contributor to all kinetic outcome models.

1.5.1.3 Chapter 4

Objective: The purpose of this final study was to determine whether a gait retraining program using real-time biofeedback of braking forces could effectively reduce peak braking force. A secondary objective was to determine the kinematic strategies used to achieve this reduction.

Hypothesis: It was hypothesized after a 15-week training program, a change in the target outcome as well as secondary kinetic outcomes would be significant ($p<0.05$). We also hypothesized that participants would preferentially choose to reduce their step length, horizontal distance from heel to centre of mass, and foot strike angle at initial contact.

1.6 Methodological approach

1.6.1 Biomechanical data collection

Continuous running is measured using kinematic (motion capture) and kinetic (force platform) methodologies. The use of an instrumented force treadmill for collection of kinetic data has numerous advantages over the force platforms used in overground studies. These include the ability to control the running speed and to measure kinetic variables over successive

strides. Accurate collection of kinetic data by a force-measuring treadmill compared to a force platform has been reported by at least two independent studies (90,91). Kinematics have also been shown to be comparable between overground and treadmill running (92).

Baseline (Chapters 2-4) and follow-up (Chapter 4) biomechanical data were collected at the Fortius Institute Biomechanics Lab with a six-camera motion analysis system (Qualisys Motion Capture Corp., Gothenburg, Sweden) on an instrumented force treadmill (Treadmetrix LLC, Park City, USA) (Figure 1.2). Participants ran in their usual running shoes and at a self-selected speed representative of a moderate intensity run (Borg Rating of Perceived Exertion = 13, indicative of "somewhat hard") (93) while three-dimensional kinetic (sampled at 2400 Hz) and kinematic (240 Hz) data were collected from three consecutive captures of 15 seconds duration each during the last minute of a single continuous running bout of 3-5 minutes. All biomechanical outcome measures were determined from the first 10 consecutive stance phases for the study limb within each of the three captures (n=30 total stance phases per participant).

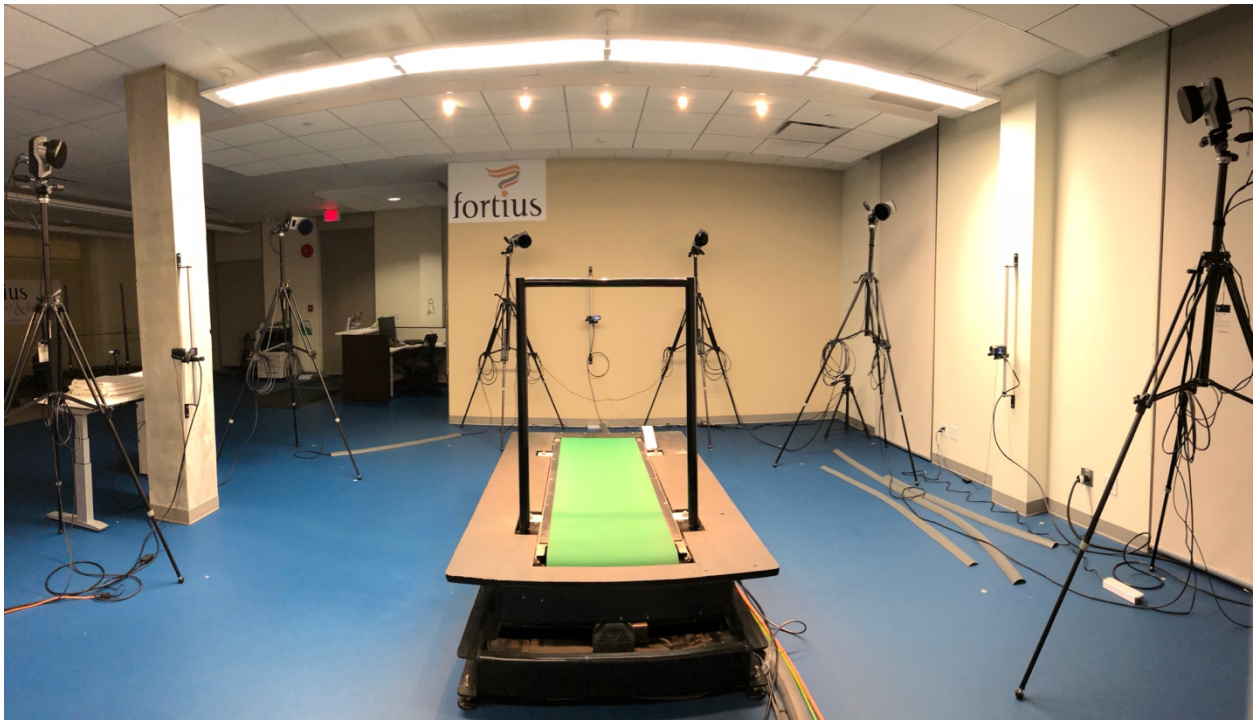


Figure 1.2 Instrumented force treadmill and six-camera motion analysis system set up.

Visual 3D software (C-Motion, Inc., Germantown, USA) was used to calculate three-dimensional kinetics and kinematics for the lower extremity according to the joint coordinate system (94). Kinetic and kinematic data were low-pass filtered using a critically-damped digital filter at a cutoff frequency of 20 Hz and 8 Hz, respectively (95). Spectral analysis showed that 95% of the power spectral density of the signal from all components of the ground reaction force was below 15 Hz, thus 20 Hz was considered a reasonable cutoff frequency. This frequency was also used in a previous study using the same instrumented force treadmill (96). Three-dimensional kinetic data from the instrumented force treadmill allowed for determination of initial contact and toe-off events (50 N threshold) and were used to determine the stance and swing phases of the gait cycle. Kinetic metrics, including three-dimensional ground reaction forces, were calculated via inverse dynamics and normalized to body weight.

1.6.2 Musculoskeletal model

A full body marker set was utilized for the studies outlined in Chapters 2 and 3. Sixty-one reflective markers were affixed to each participant prior to testing, and a static calibration trial was initially collected to form a musculoskeletal model based on MacLean et al (97) (Figure 1.3). Nineteen static/calibration markers (vertex of the head, medial elbow epicondyles, anterior superior iliac spines, greater trochanters, medial/lateral femoral condyles, medial/lateral malleoli, and first and fifth metatarsal heads were removed following the static trial and the 42 remaining markers (five on the head, C7 spinous process, acromioclavicular joints, mid-triceps, lateral epicondyles, distal radius/ulna, posterior superior iliac spines, iliac crests, clusters of four on the thigh and shank, and a triad on the heel) were by definition tracking and calibration markers as they were on for both static and dynamic trials. The study in Chapter 4 used only a lower body marker set. Forty-two reflective markers were affixed to each participant prior to testing. Sixteen static/calibration markers (anterior superior iliac spines, greater trochanters, medial/lateral femoral condyles, medial/lateral malleoli, and first and fifth metatarsal heads) were removed following the static trial, leaving 26 tracking/calibration markers (posterior superior iliac spines, iliac crests, clusters of four on the thigh and shank, and a triad on the heel) for dynamic trials.

Figure 1.3 Marker positions for static trial.
The studies outlined in Chapters 2 and 3 used a full body marker set. For bilateral analysis, 19 static/calibration markers and 42 tracking markers (total = 61) were affixed to each subject. The study in Chapter 4 used only a lower body marker set (16 static/calibration markers and 26 tracking markers (total = 42) were affixed to each subject).

The foot segment was defined by four segment definition markers: the first and fifth metatarsal head markers, and the medial and lateral ankle malleoli. The shank segment was defined by two proximal markers (medial and lateral femoral condyles) and two distal markers (medial and lateral malleoli). The thigh segment was defined by the medial and lateral femoral condyles, the anterior superior iliac spine, and the hip joint centre (98). The static position of the thigh and shank rigid plates and heel triads with respect to the segment definition markers were calculated and used to track movement during the running trials.

The origin for the foot coordinate system was located at the floor at the vertical projection of the midpoint between the two malleoli markers (the anterior-posterior axis was oriented to the vertical projection at the floor of the midpoint of the metatarsal markers, the

medial-lateral axis was oriented from the medial to lateral calcaneal markers, and the vertical axis was orthogonal to the two other axes). The origin for the shank coordinate system was located at the midpoint between femoral condyle markers (vertical axis oriented to the midpoint of the lateral and medial malleoli, anterior-posterior axis orthogonal to the plane formed by the four segment definition markers, and medial-lateral axis orthogonal to the two other axes). The origin for the thigh coordinate system was located at the hip joint centre (vertical axis oriented to the midpoint of the lateral and medial femoral condyles, anterior-posterior axis orthogonal to the plane formed by the four segment definition markers, and medial-lateral axis orthogonal to the two other axes).

Joint angles were calculated for the distal segment relative to the proximal segment using a Cardan XYZ sequence of rotations with six degrees of freedom (94). Time series data for the variables of interest were time-normalized to percentage of stance (foot strike to toe off) and ground reaction forces were amplitude-normalized to body weight. Anthropometric properties of body segments were scaled to each individual using the participant's height, mass, and segment lengths. Each model segment position was multiplied by the respective mass; centre of mass was calculated by summing these numbers and dividing by the total body mass (99).

1.6.3 Half-marathon training program intervention

Participants in the studies outlined in Chapters 2 and 4 followed a structured 15-week half-marathon training program in the community (Appendix A). This program was developed by a running coach with over 15 years of experience and supervised by a sport physiotherapist with more than 12 years of experience. The program incorporated four runs per week—two speed/hill sessions, one easy recovery run, and one long run. During weeks when there was a

lab-based biofeedback session (Chapter 4), this session took the place of the easy recovery run. The researchers had no contact with the participants during the 15-week program outside of the lab-based biofeedback sessions in Chapter 4. All participants followed the same standardized program, with weekly volumes and details of individual training sessions determined prior to study commencement. Prescribed weekly running volume increased according to the program throughout the training program from approximately 3 hours of running in Week 1 to 4.75 hours by Week 14, in preparation for a half-marathon race at the end of Week 15. Throughout the training program, participants completed a weekly online questionnaire (Appendix B) to record: any pain and its location; the number and reason for missed training days; time run per week (hours) and workouts completed; and any general comments regarding their training or pain.

Chapter 2: Kinetic risk factors of running-related injuries in female recreational runners

2.1 Introduction

Recreational running has one of the highest participation rates of any physical activity worldwide (100). Despite the recognized health benefits of running, the prevalence of running-related injury is high. Approximately half of recreational distance runners will experience a running-related injury in any given year (101). Such high injury rates impact quality of life, health, and productivity. They also discourage new runners from continuing in the sport, as a significant portion of those injured do not return to running (8). Notably, lack of running experience has been cited as one of the most important risk factors for running-related injury (4,6,102), possibly due to differences in mechanics as a result of lower training history and lack of technical skill (103). As such, novice runners are an important population to study. Training history and technical skill are often developed over structured training, usually for a race, as opposed simply to cumulative running experience. Although no definition for "novice" runners exists, we propose that a novice runner is one that has accumulated less exposure to structured training, and quantify this by race history.

Running-related injuries are multifactorial, but can be attributed primarily to anatomical or biomechanical factors, in combination with training error (104). Among biomechanical factors, excessive impact loading—typically quantified using the ground reaction force (24)—has been implicated in a number of studies (24,29,31). Several studies have investigated the relationship between running-related injury and vertical ground reaction force measures (24,27-29). Average vertical loading rate (24,28), instantaneous vertical loading rate (27-29), and

vertical impact transient (27,28) have all been associated with running-related injury in retrospective analyses. Prospective studies and a recent systematic review have produced conflicting results, with loading rate—whether measured as average or instantaneous—illustrating the closest association with running-related injury (18,20,26,31). Davis et al (18) recently conducted a prospective study and reported higher average loading rates across all injuries when injured female runners were compared to runners who had never suffered a running-related injury. In two additional prospective studies, Bredeweg et al (20) reported higher instantaneous loading rates among injured male, but not female runners, while Kuhman et al (26) did not find a difference in instantaneous loading rate between injured and uninjured runners. Finally, a large randomized controlled trial investigating the effectiveness of a gait retraining program aimed at reducing vertical loading rates reported a significant reduction in running-related injury in the intervention group (22).

Less studied has been the anterior-posterior ground reaction force exerted on the body during running. Most studies investigating this variable have primarily reported the metabolic and performance costs of greater braking forces during running (33-35). However, two studies have investigated biomechanical risk factors for tibial stress fractures retrospectively, but did not find a relationship between braking forces and injury rates (28,36). In contrast, Grimston et al (37) reported higher peak braking forces in females with a history of tibial stress fracture. In yet another contrast, Messier et al (38) reported that peak braking force was actually lower in runners with patellofemoral pain than in healthy controls. In a follow-up study (39), the authors reported that a low peak braking force was also associated with runners with iliotibial band syndrome.

The link between kinetic variables and running-related injury has prompted researchers to investigate the capacity of gait retraining to prevent injury (22,25,53). Real-time kinetic biofeedback has been the most successful tool to reduce kinetic loads (71). It is therefore important to identify the best kinetic predictors of running-related injury in order to target these interventions.

To date, there have been no prospective studies that have investigated the relationship between braking force and running-related injury. The purpose of this study was to determine the predictive capacity of specific kinetic variables on running-related injury risk. Our primary hypothesis was that average vertical loading rate would be the best predictor of running-related injury and that it would yield the highest injury hazard ratio. Our secondary hypothesis was that peak braking force would also be predictive of running-related injury.

2.2 Methods

2.2.1 Participants

A sample of female recreational runners between the ages of 18 and 60, and running for at least three months, was recruited from the local running community via flyers and social media posts. To obtain a novice running sample, inclusion was set to limit eligible participants to a history of no more than two half-marathons. Participants were excluded if they had experienced (1) a lower extremity injury in the previous three months, (2) any history of lower limb surgery, or (3) any current low back or lower extremity pain while running. Participants were recruited over four consecutive intakes. Written consent was obtained from all participants, and ethics approval was granted from the institutional Clinical Research Ethics Board.

2.2.2 Data collection

Demographics and a detailed training and injury history were collected for each participant at baseline. All participants subsequently underwent a biomechanical running analysis on an instrumented treadmill as outlined in Section 1.6.1 above. A musculoskeletal model was formed as detailed in Section 1.6.2. (Figure 1.3).

2.2.3 Training protocol

Following the baseline biomechanical running analysis, participants followed a structured 15-week half-marathon training program (Appendix A), as detailed in Section 1.6.3. Throughout the training program, participants completed a weekly online questionnaire (Appendix B) to record: any pain and its location; the number and reason for missed training days; time run per week (hours) and workouts completed; and any general comments regarding their training or pain.

2.2.4 Running-related injury definition

A modified definition of injury from a recently published consensus paper (14) was used to define a running-related injury in this study: if the injury was deemed to be running-related (due to training), overuse (not related to an acute trauma), musculoskeletal (low back and lower extremities), and reported to be the cause of missing three training days within a two-week moving window, then the participant was classified as injured (INJ). Those who completed the 15-week training program without injury were classified as uninjured (UNINJ). The injured limb was chosen as the study limb in the case of the INJ group and was randomly selected for the UNINJ group. All participants who missed at least three training runs within a two-week period

due to pain were assessed by the principal investigator (a sport physiotherapist) for injury diagnosis using the criteria discussed above. Incidence of running-related injury was calculated as the number of new injuries reported per 100 runners at risk.

2.2.5 Data analysis

Biomechanical data were analyzed using Visual 3D software (C-Motion, Inc., Germantown, MD). Kinetic and kinematic data were low-pass filtered using a critically-damped digital filter at a cutoff frequency of 20 Hz and 8 Hz, respectively (95). Spectral analysis showed that 95% of the power spectral density of the signal from all components of the ground reaction force was below 15 Hz, thus 20 Hz was considered a reasonable cutoff frequency. This frequency was also used in a previous study using the same instrumented force treadmill (96). Initial contact and toe-off events were identified by a vertical ground reaction force threshold of 50 N and were used to determine the stance and swing phases of the gait cycle. Kinetic variables were normalized to body weight.

All biomechanical outcome measures were determined from the first 10 consecutive stance phases for the study limb within each of the three captures (n=30 total stance phases per participant). Kinetic outcomes included vertical impact transient, average vertical loading rate, instantaneous vertical loading rate, active peak, peak braking force, and vertical impulse. The vertical impact transient was defined as a distinct, short-duration change in the magnitude of the vertical ground reaction force during loading between initial contact and maximum vertical ground reaction force (105). Average vertical loading rate and instantaneous vertical loading rate were calculated as the average and peak slopes, respectively, during the middle 60% of the period between initial contact and the vertical impact transient. The active peak was the

maximum value on the vertical ground reaction force curve. Peak braking force was defined as the maximum posterior force observed and vertical impulse was calculated as the integral of the vertical ground reaction force from initial contact to toe-off (see Figure 1.1 for visualizations of these measures). Foot strike pattern was determined by a method proposed by Irene Davis (personal communication). A midfoot strike was defined as a foot strike angle of 0° (foot flat) +/- 3 SEM of the overall sample; a forefoot strike was defined as a foot strike angle <3 SEM; and a rearfoot strike was defined as a foot strike angle >3 SEM. For the purpose of comparison, midfoot and forefoot strikes were combined into a non-rearfoot strike category.

2.2.6 Statistical analysis

Exposure time (measured in hours of running exposure) was calculated from the start of the running program until the runner first reported an injury (INJ) or until the end of the program (UNINJ). Participants lost to follow-up were right-censored at the point of their last logged run, while those suffering an acute or non-running-related injury were included in the model as a competing risk (106). Kinetic variables were first converted from continuous to ordinal variables based on tertiles (T1, T2, or T3). We chose to use tertiles in order to have an adequate number of participants per group as well as for ease of comparison (high, medium, and low groups). Each kinetic predictor was then analyzed in a univariable model both adjusted (for age and baseline preferred speed) and unadjusted to observe the independent relationship with running-related injury. Cox proportional hazard models with competing risks were fit for each variable independently and ranked in order of ascending Akaike information criteria (AIC). This order was then used to enter predictors into a forward stepwise multivariable model. Generalized R^2 and AIC were calculated, with the lowest AIC indicating the best predictive multivariable model.

Hazard ratios (HR) were calculated between individual tertiles. The proportional hazards assumption was evaluated with log-minus-log plots. All statistical analyses were performed using SAS version 9.4 (SAS Institute, Cary, NC).

2.3 Results

Seventy-four participants met the inclusion criteria and underwent the baseline biomechanical assessment (Figure 2.1). Two participants were excluded based on the absence of a flight phase, and one was excluded due to data collection errors. Six participants were unable to start the running program and were excluded from analysis. Therefore, 65 participants were included in the final analysis (Table 2.1). There were no significant differences between INJ and UNINJ groups for any of the demographic variables or baseline preferred speed.

Table 2.1 Demographics of the analyzed groups.
Data are reported as mean +/- SD) for all variables except number of previous half-marathons, which are reported as median (interquartile range), and foot strike pattern, which are reported as frequency in percent.

	Total (n=65)	INJ (n=22)	UNINJ (n=33)	Other (n=10)
Age (years)	36.3 +/- 8.4	34.7 +/- 7.8	37.4 +/- 8.2	36.4 +/- 10.3
Body mass index (kg/m^2)	22.7 +/- 2.5	22.5 +/- 1.9	22.6 +/- 2.6	23.5 +/- 3.2
Running experience (years)	7.8 +/- 7.2	6.3 +/- 5.2	9.2 +/- 8.9	6.9 +/- 4.2
Prior weekly volume (km)	17.9 +/- 12.2	17.1 +/- 8.0	18.0 +/- 13.0	19.3 +/- 17.3
No. of previous half-marathons	1 (2)	1 (2)	0 (1)	1 (1)
Baseline preferred speed (m/s)	2.47 +/- 0.33	2.51 +/- 0.34	2.43 +/- 0.33	2.49 +/- 0.36
Foot strike pattern (RF/NRF) (%)	73.8/26.2	72.7/27.2	72.7/27.2	80.0/20.0
Exposure time (hours)	29.51 +/- 17.32	17.46 +/- 9.81	43.46 +/- 10.48	9.97 +/- 5.10
Exposure time (weeks)	10.48 +/- 5.16	6.34 +/- 3.44	15.00 +/- 0.00	4.65 +/- 2.68
Average weekly exposure (hours)	2.69 +/- 0.81	2.43 +/- 0.44	2.92 +/- 0.68	2.51 +/- 1.45

INJ, running-related injury; UNINJ, no injury by training program completion date; Other, non-running-related or acute injury (n=3) or loss to follow-up (n=7); RF, rearfoot; NRF, non-rearfoot.

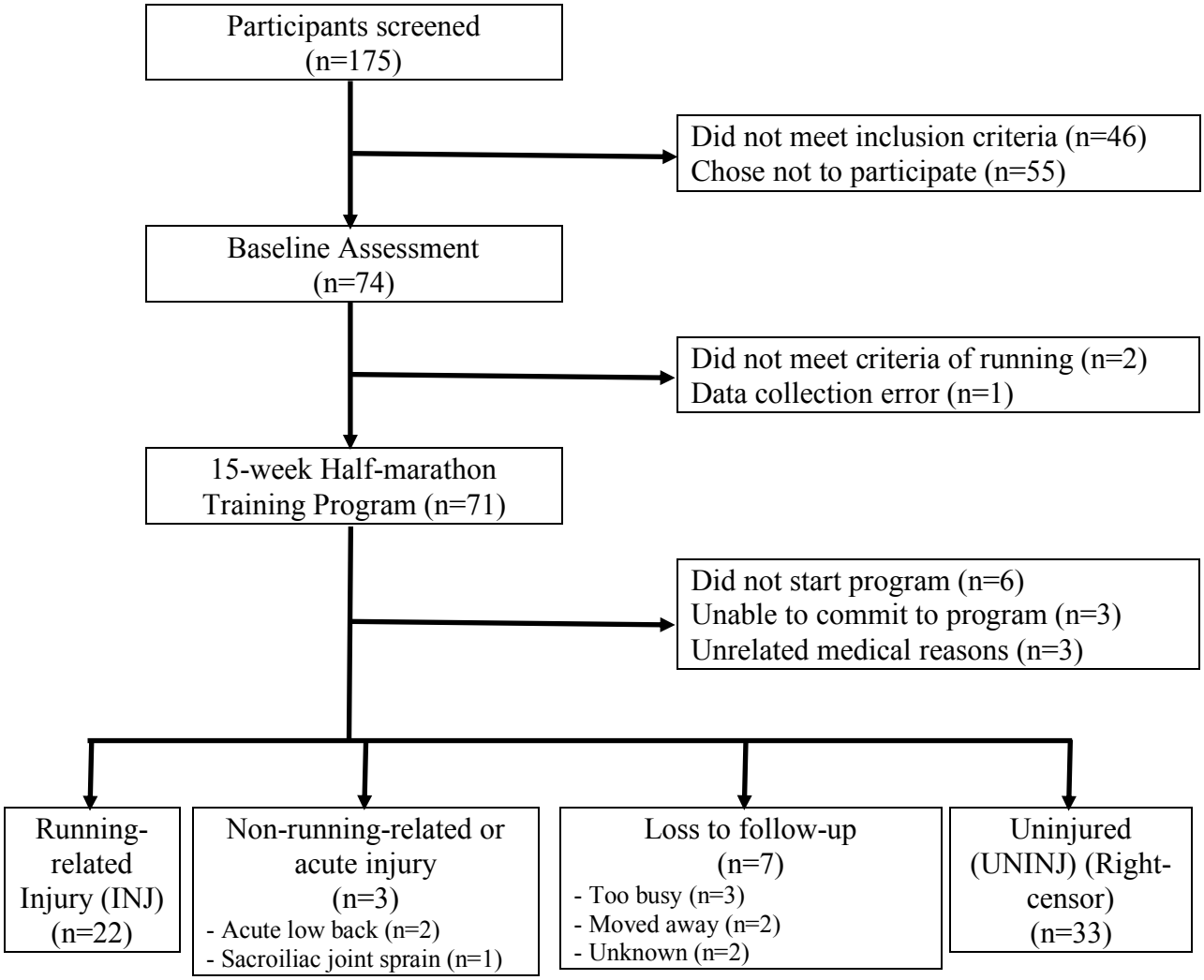


Figure 2.1 Flow of participants through study.

Twenty-two participants (33.8%) were diagnosed with a running-related injury (INJ) with a mean exposure time of 17.46+/-9.81 hours. Thirty-three runners (50.8%) completed the 15-week training program without injury (UNINJ), with a mean exposure time of 43.46+/-10.48 hours. Ten participants (15.4%) did not complete the training program due to: acute or non-running-related injury (n=3), or loss to follow-up (n=7). Reasons for loss to follow-up are displayed in Figure 2.1. The most common injuries (Table 2.2) were medial tibial stress syndrome (n=6), followed by iliotibial band syndrome (n=3), tendinopathy (n=3), and muscle strain (n=3).

Table 2.2 Number of injuries (n=22) by type and location for the INJ group.

Injury type	Number of cases (%)	Exposure time (hours)
Medial tibial stress syndrome	6 (27.3)	25.48 +/- 11.07
Iliotibial band syndrome	3 (13.6)	20.78 +/- 5.19
Tendinopathy	3 (13.6)	14.23 +/- 5.76
Muscle strain	3 (13.6)	9.62 +/- 3.89
Piriformis syndrome	2 (9.1)	10.65 +/- 6.51
Patellofemoral pain	1 (4.5)	23.45 +/- 0.00
Plantar fasciitis	1 (4.5)	11.25 +/- 0.00
Other	3 (13.6)	13.78 +/- 13.65
Injury location		
Knee	9 (40.9)	18.12 +/- 7.99
Lower leg	8 (36.4)	20.09 +/- 10.66
Foot/ankle	3 (13.6)	7.79 +/- 3.50
Hip	2 (9.1)	10.65 +/- 6.51

Exposure time reported as mean +/- SD; INJ, running-related injury.

The anterior-posterior ground reaction force ensemble averages for peak braking force tertiles are shown in Figure 2.2. The univariable analysis revealed that peak braking force was the only kinetic variable that was a significant predictor of running-related injury. Specifically, runners in the highest tertile (T3; peak braking force >0.27 BW) were injured at 3.79 (95% CI :1.44-10.01) times the rate of those in T2 (0.23-0.27 BW), and 5.81 (95% CI: 1.63-20.64) times the rate of those in T1 (<0.23 BW) (Table 2.3). When peak braking force was adjusted for age

and baseline preferred speed, participants with the greatest peak braking force (T3) were injured at 5.08 (95% CI: 1.71-15.03) times the rate of those in T2 and 7.98 (95% CI: 2.08-30.51) times the rate of those in T1 (Table 2.4). When analyzed in a multivariable model (Table 2.5), no other kinetic variables made a significant contribution to predicting injury that had not already been accounted for by peak braking force alone. Fourteen of the 22 runners in the highest tertile (T3) suffered a running-related injury, compared to 5 in T2 and only 3 in T1.

We also conducted a post hoc power analysis to show that the study was adequately powered to detect the observed effect. The SD of peak braking force/.08 in our data was 0.519, and 33.8% of the n=65 subjects experienced an overuse injury. Therefore, we would have had 100% power to detect an effect of peak braking force of 7.98 per 0.08 units (T1 vs. T3), via 2-sided test at p=0.05. The SD of peak braking force /.05 in our data was 0.831, therefore we would have had 100% power to detect an effect of peak braking force of 5.08 per 0.05 units (T2 vs. T3), via 2-sided test at p=0.05. The interval widths of .08 and .05 were derived from the quantiles at the midpoints of the relevant tertiles.

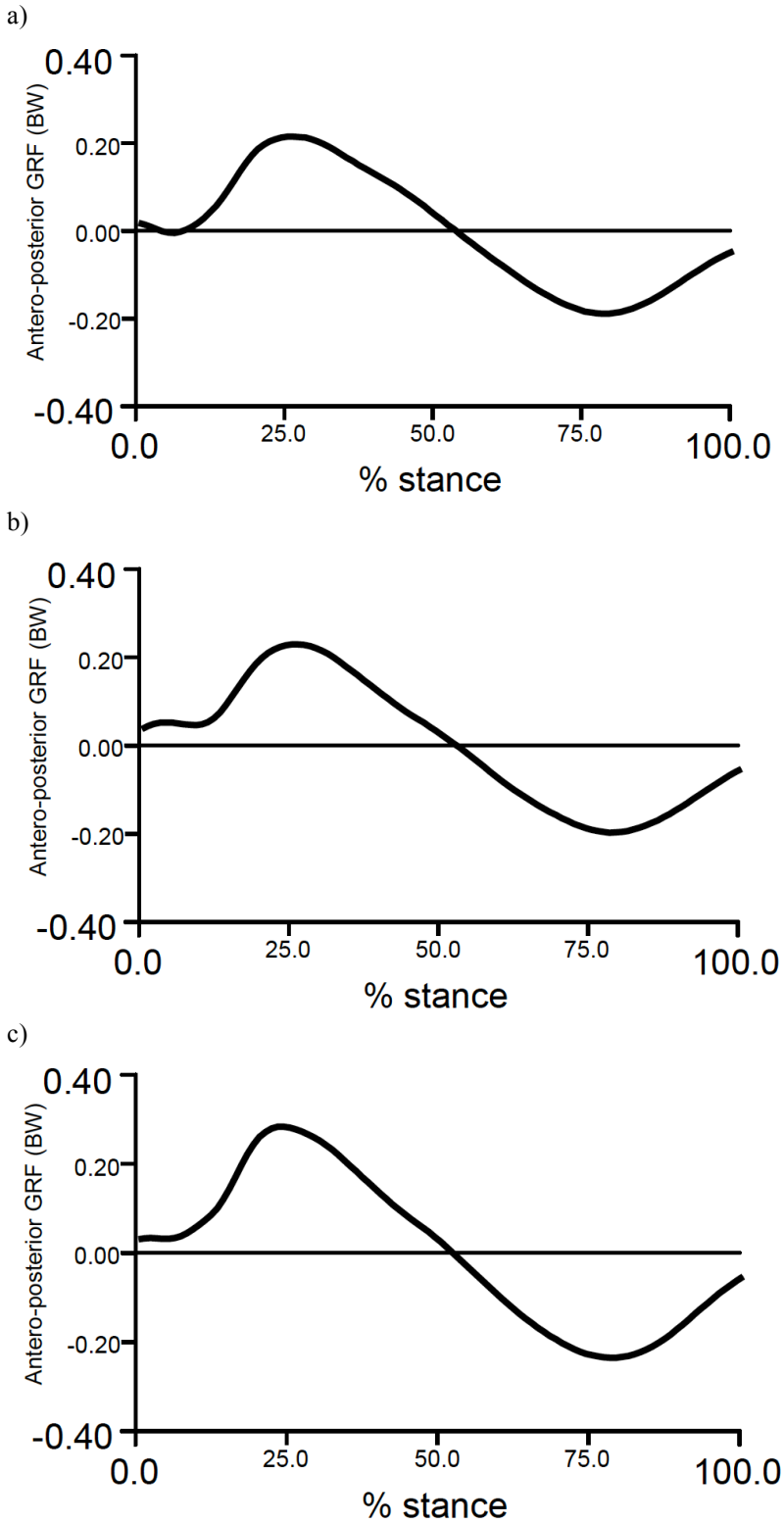


Figure 2.2 Anterior-posterior ensemble GRF versus time curves for PBF tertiles 1 (a), 2 (b), and 3 (c). Braking represented as positive. GRF, ground reaction force; PBF, peak braking force; BW, body weights.

Table 2.3 Unadjusted univariable model hazard ratios.
Kinetic predictors of running-related injury with 95% CI. Predictor variables were split into tertiles (T1, T2, T3).

	Values			Unadjusted HR		
	T1	T2	T3	T3 to T2	T2 to T1	T3 to T1
VIT (BW)	<1.40	1.40-1.59	>1.59	0.94 (0.37-2.38)	1.62 (0.52-5.07)	1.52 (0.51-4.57)
AVLR (BW/s)	<40.85	40.85-50.46	>50.46	1.49 (0.57-3.93)	1.57 (0.50-4.95)	2.35 (0.84-6.58)
IVLR (BW/s)	<51.99	51.99-64.71	>64.71	1.13 (0.43-2.95)	1.34 (0.48-3.80)	1.52 (0.53-4.31)
AP (BW)	<2.09	2.09-2.32	>2.32	0.75 (0.28-2.00)	1.03 (0.37-2.85)	0.78 (0.28-2.19)
PBF (BW)	<0.23	0.23-0.27	>0.27	3.79 (1.44-10.01)[†]	1.53 (0.37-6.38)	5.81 (1.63-20.64)[*]
VI (BW*s)	<0.35	0.35-0.37	>0.37	0.74 (0.29-1.91)	2.12 (0.73-6.13)	1.57 (0.54-4.57)

[†] p=0.007
[*] p=0.007
HR, Hazard Ratio; VIT, vertical impact transient; AVLR, average vertical loading rate; IVLR, instantaneous vertical loading rate; AP, active peak; PBF, peak braking force (braking represented as positive value); VI, vertical impulse; BW, body weight; s, second.

Table 2.4 Adjusted univariable model hazard ratios.
Kinetic predictors of running-related injury adjusted for age and baseline preferred speed injury with 95% CI. Predictor variables were split into tertiles (T1, T2, T3).

	Values			Adjusted HR		
	T1	T2	T3	T3 to T2	T2 to T1	T3 to T1
VIT (BW)	<1.40	1.40-1.59	>1.59	1.03 (0.40-2.65)	1.42 (0.40-5.05)	1.46 (0.48-4.41)
AVLR (BW/s)	<40.85	40.85-50.46	>50.46	1.79 (0.64-4.96)	1.40 (0.44-4.46)	2.50 (0.83-7.50)
IVLR (BW/s)	<51.99	51.99-64.71	>64.71	1.19 (0.41-3.46)	1.26 (0.45-3.52)	1.49 (0.44-5.08)
AP (BW)	<2.09	2.09-2.32	>2.32	0.59 (0.20-1.77)	0.92 (0.29-2.91)	0.55 (0.19-1.60)
PBF (BW)	<0.23	0.23-0.27	>0.27	5.08 (1.71-15.03)[†]	1.57 (0.38-6.47)	7.98 (2.08-30.51)[*]
VI (BW*s)	<0.35	0.35-0.37	>0.37	0.74 (0.28-1.94)	2.74 (0.75-10.01)	2.02 (0.47-8.63)

[†] p=0.003
[*] p=0.002
HR, Hazard Ratio; VIT, vertical impact transient; AVLR, average vertical loading rate; IVLR, instantaneous vertical loading rate; AP, active peak; PBF, peak braking force (braking represented as positive value); VI, vertical impulse; BW, body weight; s, second.

Table 2.5 Multivariable analysis for (a) adjusted and (b) unadjusted kinetic predictors of running-related injury. † Indicates best model based on Akaike Information Criteria.

(a)

Model	Variables in Model	Generalized R^2	Akaike Information Criteria (AIC)
1†	PBF	0.21	161.079
2	Model 1+VI	0.25	161.126
3	Model 2+AVLR	0.25	164.890
4	Model 3+AP	0.34	161.210
5	Model 4+VIT	0.36	163.266
6	Model 5+IVLR	0.42	160.964

(b)

Model	Variables in Model	Generalized R^2	Akaike Information Criteria (AIC)
1†	PBF	0.18	159.512
2	Model 1+AVLR	0.18	163.197
3	Model 2+VI	0.23	163.324
4	Model 3+VIT	0.23	166.828
5	Model 4+IVLR	0.26	168.792
6	Model 5+AP	0.38	161.197

VIT, vertical impact transient; AVLR, average vertical loading rate; IVLR, instantaneous vertical loading rate; AP, active peak; PBF, peak braking force; VI, vertical impulse; BW, body weight; s, second.

2.4 Discussion

The purpose of this prospective observational study was to examine the predictive capacity of kinetic variables on running-related injuries. Our primary hypothesis was that average vertical loading rate would be the best predictor of running-related injury. Though the univariable analysis revealed a trend toward higher rates of injury for higher average vertical loading rate, this did not reach statistical significance. Further, it was not a statistically significant contributor to the multivariable model. Taken together, these refute our primary hypothesis. However, our secondary hypothesis that peak braking force would also be a significant predictor of running-related injury was accepted. In fact, the highest tertile (T3) of peak braking force was associated with a five-fold increase in injury rate when adjusted for age and baseline preferred speed compared to the middle tertile (T2) and eight times the rate of those within the lowest tertile (T1) of peak braking force.

2.4.1 Injuries

The distribution of injuries was similar to previous studies with female populations. The knee and lower leg made up more than three-quarters of all injuries, which is consistent with findings by Taunton et al (107). In addition, Lopes et al (108) reported in a systematic review that medial tibial stress syndrome had the highest incidence among running-related injury, which is in agreement with results from this cohort. While the types of injuries seen in this sample are similar to previous investigations, some common running-related injuries (e.g. patellofemoral pain) did not occur as frequently as previously reported.

2.4.2 Kinetic Risk Factors

Several prospective studies have investigated the relationship between average vertical loading rate and running-related injury with conflicting results (18,20,26). However, a promising recent interventional study produced a significant decrease in injury risk with a gait retraining program focused specifically on reducing the vertical loading rate (22). In our cohort, when runners in the highest tertile of average vertical loading rate (T3) were compared to lowest tertile average vertical loading rate runners (T1), there was a non-statistically significant trend toward greater injury risk (HR 2.50; 95% CI: 0.83-7.50; p=0.102).

Our findings are in agreement with two previously published prospective studies investigating the relationship of impact loading and running-related injuries. Bredeweg et al (20) reported that while baseline instantaneous vertical loading rate was prospectively higher in males who became injured, there was no difference between injured and uninjured females. In a smaller study, Kuhman et al (26) reported no difference between prospectively injured and uninjured well-trained runners on the basis of instantaneous vertical loading rate. On the other

hand, Davis et al (18) reported that runners with high average vertical loading rate were at a greater risk of developing a running-related injury requiring medical attention than those runners who had never sustained a running-related injury. One difference to note is that average vertical loading rate was much higher in the latter study than in our study, likely due in part to the higher baseline testing speed (3.7 m/s). However, it was important to us to capture participants at their preferred speed to mimic running performance outside of the lab setting. It should also be noted that in the study by Davis et al (18), there was no difference between injured and uninjured runners on the whole—it was only when two subgroups ("medically diagnosed injuries" and "never sustained a running injury") were compared that a difference in average vertical loading rate was seen. One limitation with both of the above studies and our own is the fact that the final analysis included all injuries. Historically, average vertical loading rate has been retrospectively associated with specific injuries (e.g. tibial stress fracture (24,28)), and significance may be diminished when pooled with other injuries (e.g. anterior knee pain, tendinopathy (31)) that may not be as influenced by loading rate.

A novel finding in our study was that a greater peak braking force was associated with a significantly higher injury hazard ratio. Previous studies (33-35) have examined the relationship of peak braking force to running economy, but none have prospectively investigated its relationship to running-related injuries. In the studies that have investigated peak braking force with retrospective injury cohorts, it is interesting to note that all with the exception of one (37) reported either no difference or that peak braking force was actually lower in the injured population (28,36,38,39). This could be explained by a reluctance to braking in a population that has already sustained an injury rather than implying causation. Indeed, a higher peak braking force fits with injury prediction theories. It is known that bones do not withstand shear

(horizontal) forces as well as they withstand compressive (vertical) forces, despite the magnitudes being several times greater for the latter (40,41). Shear forces applied to the foot and lower leg may also increase the risk of certain soft tissue injuries (42). Braking forces have also been studied in relation to changes in lower extremity posture at initial contact. Heiderscheit et al (48) demonstrated that braking impulse increased the further the foot landed anteriorly relative to the centre of mass. This posture was also linked to increased energy absorption at the knee and hip.

One strength of our study and a difference between our study population and others (18,20,28) is the inclusion of all foot strike patterns. Interestingly, there was no difference in foot strike pattern between INJ and UNINJ groups ($p=1.000$) and no relationship between foot strike pattern and peak braking force in our cohort ($p=0.844$). In contrast, Boyer et al (54) demonstrated that forefoot strike runners had peak braking forces 450% greater than in rearfoot strike runners. However, Nordin et al (42) did not find differences of this scale between foot strike patterns. There is the possibility that by excluding non-rearfoot strike runners in previous studies, peak braking force may have escaped notice as a determinant for running-related injury. Despite being commonly asserted, a rearfoot strike pattern has been associated with higher injury rates by one study only (49). That study was retrospective in design, used a very specific sample of runners (competitive Division 1 college cross-country runners), and had a relatively small sample size (109). Aside from the aforementioned study, we are only aware of indirect links between foot strike pattern and injury, based on the assumed causative association between vertical loading rate and injury, and the typical vertical loading profiles of rearfoot versus forefoot strike runners. What is more likely is that the location of injury changes with foot strike pattern (42), but there are no large prospective studies to date. Indeed, in 3 large epidemiological

studies, there were no statistically significant differences in injury rate between rearfoot and non-rearfoot strike runners (109). Therefore, until further large prospective studies are conducted, only inferences based on vertical and anterior-posterior force profiles can be made.

There are some limitations to this study. Firstly, our sample includes females only. This was a conscious decision in recognition of the differences in biomechanical risk factors between males and females (20). However, we encourage future research of this nature in male runners. Secondly, we computed hazard ratios for all prospective injuries as opposed to specific injuries. While this may make the results more difficult to link to specific conditions, it does make our findings more generalizable to all injury conditions as a whole. Thirdly, our analysis was performed on a treadmill while most of our participants conducted their training overground. While kinetics have been shown to be similar between treadmill and overground running (90,91), some differences in kinematics have been documented (decreased step length and heel to centre of mass distance (110), more flexed knee at initial contact (110), and a more midfoot/forefoot strike on a treadmill (110,111)). Finally, many external factors, such as changes in elevation, weather, nutritional status, footwear, running surface, etc. may influence the development of running-related injuries. These variables were beyond the scope of our analysis, but we cannot deny their potential effect on our outcomes.

2.5 Conclusions

To our knowledge, this is the first study to demonstrate prospectively that peak braking force is associated with an increased risk of running-related injury. Our findings also contribute to the debate over the importance of average vertical loading rate as a factor in the development of running-related injuries. The relationship between kinetic variables and running-related injury

has prompted researchers to investigate the role of gait retraining via kinetic real-time biofeedback (22,25,53). These studies have been largely successful at reducing kinetic loads (71). It is therefore important to identify the best kinetic predictors of running-related injury in order to target these interventions. Our findings suggest that the use of peak braking force may be a more effective target for gait retraining than vertical loading rate and we encourage researchers to explore this as a real-time biofeedback cue in future studies. Further investigation into the kinematic correlates of peak braking force (such as step length/frequency, heel to centre of mass distance, etc.) may also aid in generating effective gait retraining interventions that could be implemented in a clinical setting where real-time biofeedback is not available.

Chapter 3: Kinematic correlates of kinetic risk factors of running-related injury

3.1 Introduction

Running is one of the most popular activities worldwide, with numerous health advantages. Running has benefits in the prevention of obesity, hypertension, type 2 diabetes, osteoarthritis, respiratory disease, cancer, and disability (2). Even in low doses, running is associated with a substantial reduction in cardiovascular and all-cause mortality (2). However, injury rates are high and have not decreased appreciably in the decades since monitoring began (4,8,107). While the etiology of running injuries is multifactorial (104), biomechanical factors—primarily kinetic factors associated with the loading phase of running—have been linked to the development of running-related injury (18,20,24,27-29,31). For instance, a high vertical loading rate (whether measured as average or instantaneous) has been cited as a risk factor for tibial stress fracture in two systematic reviews (24,31). The review by van der Worp et al (31) expanded on this analysis to show that vertical loading rate was a risk factor in studies where all running-related injuries were included and this has been supported by a prospective study by Davis et al (18). As seen in Chapter 2, peak braking force may also be an important risk factor for running-related injury, with higher braking forces resulting in risk of injury five to eight times that of lower braking forces (112).

Recently, running gait retraining has become a popular mode of treatment for running injuries, with promising results (22,66). Several studies have shown the ability to lower vertical loading rates through a gait retraining intervention with real-time biofeedback of vertical ground reaction force or tibial acceleration (22,69,70). To date, the most effective interventions have

relied on lab-based feedback of kinetic metrics (71). However, in a clinical setting, it is not always feasible to provide real-time feedback of ground reaction force variables due to constraints on equipment, costs, and analytic methods. Fortunately, many kinematic variables can be measured and modified in a clinical setting using 3D motion capture or even 2D video (76,77). To better design and implement gait retraining interventions, it is important to understand which kinematic variables contribute to kinetic risk factors of running-related injury.

The posture of the lower extremity at initial contact and during the loading phase has been reported to influence the magnitude and rate of loading (48,61,62). In a step rate intervention, Heiderscheit et al (48) found that decreased step frequency—or greater step length—resulted in a higher braking force and active peak. The increased step length was accompanied by an increase in the horizontal distance between the heel and centre of mass at initial contact. Further, Mercer et al (52) reported that changes in step length, but not step frequency affected shock attenuation in runners. They posited that shock attenuation, by way of tibial acceleration magnitude, was affected by changes in step length due to alterations in lower extremity posture and compliance at initial contact. Lieberman et al (61) noted that increases in step length can be achieved either by a longer flight phase or by landing with a more extended lower extremity with a greater heel to centre of mass distance at initial contact (often referred to as "overstriding"). Furthermore, the unique combination of hip and knee flexion at initial contact can affect the appearance of this overstride, with greater knee extension and hip flexion—resulting in an increase in shank angle and horizontal distance from heel to centre of mass—producing greater braking force and impact peak magnitude (61). Heiderscheit et al (48) observed a decrease in knee flexion and an increase in hip flexion at initial contact with increasing step length, but did not report the relationship between these kinematic variables and

the kinetic outcomes. In a clinical context, increased step length, heel to centre of mass distance, hip flexion angle at initial contact, and shank angle are all believed to be measures of overstriding. Relating these measures and their contribution to kinetic risk factors of running-related injury, therefore, is an important step to be able to inform clinical guidelines for gait retraining.

Foot strike angle at initial contact has also been reported to change significantly with greater changes (+/-10%) in step length, with a more dorsiflexed ankle at initial contact at longer step lengths (48). In a study by Wille et al (62), foot strike angle at initial contact was present in all models used to predict kinetic outcomes, indicating its important influence on the loading phase of running. Vertical ground reaction force measures (vertical impact transient, average vertical loading rate, and instantaneous vertical loading rate) have been consistently reported to be lower in runners with lower foot strike angles (53,54,82). Given the association between foot strike angle and loading, it is likely that foot strike angle could explain a significant amount of the variance in kinetic outcomes.

Debate in the literature and among clinicians exists as to how runners should be instructed to achieve a reduction in kinetic variables associated with injury, with experts disagreeing on the importance of reducing overstride versus changing foot strike pattern (66). While the reduction of an overstride is considered by many to be one of the most beneficial gait retraining strategies (66), evidence to support the relationship between overstriding and running-related injury is lacking. Further, while a definition of what constitutes an overstride (e.g. increased heel to centre of mass distance, greater shank angle, etc.) is important, we suggest that more important is the kinetic consequence of that overstride (e.g. increased peak braking force and vertical loading rate). Given the suggested importance of overstriding in running-related

injury pathogenesis, knowledge of specific kinematic variables that relate to overstriding—and are predictive of kinetic risk factors—could inform clinic-based gait retraining programs aimed at reducing risk factors of running-related injury.

The purpose of this study, therefore, was to determine if kinetic risk factors of running-related injury could be estimated from specific kinematic variables related to overstriding. We hypothesized that the following kinematic variables—greater step length, landing with a more flexed hip, a greater horizontal distance between the heel and centre of mass, and greater shank angle at initial contact—would significantly contribute to the variance in peak braking force, vertical impact transient, average vertical loading rate, and instantaneous vertical loading rate during running. We also hypothesized that foot strike angle would be a significant contributor to all kinetic outcome models.

3.2 Methods

3.2.1 Participants

Data presented in this Chapter are from the baseline testing session in Chapter 2 (112). As stated in Chapter 2, a sample of female recreational runners between the ages of 18 and 60, and running for at least three months was recruited from the local running community via flyers and social media posts. Participants were excluded if they had experienced (1) a lower extremity injury in the previous three months, (2) any history of lower limb surgery, or (3) any current low back or lower extremity pain while running. Written consent was obtained from all participants and ethics approval was granted from the institutional Clinical Research Ethics Board.

3.2.2 Data collection

Demographics and a detailed training and injury history were collected for each participant prior to undergoing a biomechanical running analysis on an instrumented treadmill as outlined in Section 1.6.1 above. A static calibration trial was initially collected to form a musculoskeletal model as described in Section 1.6.2. (Figure 1.3).

3.2.3 Data analysis

Biomechanical data were analyzed using Visual 3D software (C-Motion, Inc., Germantown, USA). Kinetic and kinematic data were low-pass filtered using a critically-damped digital filter at a cutoff frequency of 20 Hz and 8 Hz, respectively (95). Spectral analysis showed that 95% of the power spectral density of the signal from all components of the ground reaction force was below 15 Hz, thus 20 Hz was considered a reasonable cutoff frequency. This frequency was also used in a previous study using the same instrumented force treadmill (96). Initial contact and toe-off events were identified by a vertical ground reaction force threshold of 50 N and were used to determine the stance and swing phases of the gait cycle. Kinetic variables were normalized to body weight.

The study limb was chosen based on the same criteria as described in Chapter 2 (the limb that was prospectively injured or, in the absence of injury, randomly selected). All biomechanical outcome measures were determined from the first 10 consecutive stance phases for the study limb within each of the three captures (n=30 total stance phases per participant). Kinetic outcomes were selected based on their established importance in the running-related injury literature, and consisted of vertical impact transient (27,28), average vertical loading rate (24,28), instantaneous vertical loading rate (27-29), and peak braking force (Chapter 2) (112).

The vertical impact transient was defined as a distinct, short-duration change in the magnitude of the vertical ground reaction force during loading between initial contact and maximum vertical ground reaction force (105). Average vertical loading rate and instantaneous vertical loading rate were calculated as the average and peak slopes, respectively, during the middle 60% of the period between initial contact and the vertical impact transient. Peak braking force was defined as the maximum posterior force observed from initial contact to 50% of stance. Kinematic outcomes included step length; hip flexion angle at initial contact; the horizontal distance from the heel to the centre of mass; shank angle at initial contact; and foot strike angle. Kinematic variable selection was based on ease of measurement in a clinical setting and on potential use for running assessment and retraining.

3.2.4 Statistical analysis

Descriptive statistics (means and standard deviations) were calculated for all demographic variables. We used scatterplots and Pearson correlation coefficients to examine the bivariate relationships among baseline preferred speed, kinematic variables, and kinetic outcomes. We used stepwise multiple linear regression to create forced entry models evaluating the amount of variance in each kinetic outcome explained by baseline preferred speed and the five kinematic variables. Speed was entered into the model first to control for its effect on kinetic outcomes (28,63). The kinematic variable with the highest significant partial correlation coefficient was then added to the equation, repeating this process until the addition of more variables did not significantly improve the prediction accuracy of the model (113). Regression diagnostics were conducted on all models using residual analysis to ensure that the equations

satisfied the assumptions for linear modelling. All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, USA).

3.3 Results

Seventy-four female participants met the inclusion criteria and underwent the baseline biomechanical assessment. Two participants were excluded based on the absence of a flight phase and one was excluded due to data collection errors. As a result, seventy-one participants (mean age 36.8 +/- 8.3 years; BMI 22.9 +/- 2.5 kg/m^2; baseline preferred speed 2.45 +/- 0.33 m/s) were included in the final analysis. Participant running gait data are presented in Table 3.1.

Table 3.1 Kinetic and kinematic running gait data of the participants (n=71).

	Mean +/- SD	Min, max
PBF (BW)	0.253 +/- 0.041	0.167, 0.362
AVLR (BW/s)	45.52 +/- 11.89	21.33, 70.24
IVLR (BW/s)	57.49 +/- 15.47	27.46, 92.59
VIT (BW)	1.48 +/- 0.25	0.95, 2.17
Step Length (m)	0.89 +/- 0.10	0.68, 1.15
Foot strike angle (°)	4.34 +/- 7.05	-21.04, 16.70
Horizontal Distance from Heel to COM (m)	0.102 +/- 0.030	0.02, 0.18
Shank angle (°)	5.96 +/- 2.58	-0.05, 10.23
Hip flexion angle at initial contact (°)	30.96 +/- 5.79	18.19, 46.75

PBF, peak braking force (braking represented as positive values); AVLR, average vertical loading rate; IVLR, instantaneous vertical loading rate; VIT, vertical impact transient; COM, centre of mass. Foot strike angle measured from the horizontal with a positive angle a more rearfoot strike. Shank angle measured from the vertical with a positive angle indicating that the ankle is anterior to the knee.

3.3.1 Correlation coefficients

Pearson product moment correlations between kinetic risk factors, baseline preferred speed, and kinematic predictors are reported in Table 3.2. Peak braking force had a high positive correlation with step length ($r=0.80$; $p<0.05$), and low positive correlations with horizontal distance from heel to centre of mass ($r=0.33$; $p<0.05$) and hip flexion angle ($r=0.36$; $p<0.05$)—indicating higher braking forces with longer step lengths, greater heel to centre of mass distance,

and increased hip flexion at initial contact. Step length had a low positive correlation with average vertical loading rate ($r=0.35$; $p<0.05$) and instantaneous vertical loading rate ($r=0.36$; $p<0.05$), with instantaneous vertical loading rate also having a low positive correlation with hip flexion angle ($r=0.31$; $p<0.05$)—indicating greater vertical loading rates with longer step lengths and increased hip flexion at initial contact. Vertical impact transient had low negative correlations with horizontal distance from heel to centre of mass ($r=-0.40$; $p<0.05$) and shank angle ($r=-0.32$; $p<0.05$)—indicating higher vertical impact transient magnitude with decreased heel to centre of mass distance and a more vertically-oriented shank. All kinetic outcomes had low to moderate positive correlations ($p<0.05$) with baseline preferred speed (peak braking force: $r=0.67$; average vertical loading rate: $r=0.42$; instantaneous vertical loading rate: $r=0.48$; vertical impact transient: $r=0.30$), indicating higher magnitudes and rates with increased speed.

Table 3.2 Pearson product moment correlations (95% confidence interval) among kinetic risk factors, baseline preferred speed, and kinematic variables**.**

	Baseline Preferred Speed	Step Length	Foot strike angle	Horizontal distance from heel to COM	Shank angle	Hip flexion angle at initial contact
Step Length	0.88* (0.81, 0.92)					
Foot strike angle	-0.10 (-0.32, 0.14)	-0.12 (-0.34, 0.12)				
Horizontal distance from heel to COM	0.49* (0.29, 0.65)	0.57* (0.39, 0.71)	0.34* (0.11, 0.53)			
Shank angle	0.22 (-0.02, 0.43)	0.26* (0.03, 0.47)	-0.00 (-0.24, 0.23)	0.54* (0.35, 0.69)		
Hip flexion angle at initial contact	0.37* (0.15, 0.55)	0.32* (0.09, 0.51)	0.16 (-0.08, 0.38)	0.16 (-0.07, 0.38)	-0.10 (-0.32, 0.14)	
Peak Braking Force	0.67* (0.51, 0.78)	0.70* (0.55, 0.80)	0.10 (-0.14, 0.32)	0.33* (0.11, 0.53)	0.03 (-0.20, 0.26)	0.36* (0.14, 0.55)
Average Vertical Loading Rate	0.42* (0.21, 0.60)	0.35* (0.13, 0.54)	0.27* (0.04, 0.47)	0.06 (-0.17, 0.29)	0.05 (-0.19, 0.28)	0.27* (0.04, 0.47)
Instantaneous Vertical Loading Rate	0.48* (0.28, 0.64)	0.36* (0.13, 0.54)	0.25* (0.02, 0.46)	0.01 (-0.22, 0.24)	-0.04 (-0.27, 0.20)	0.31* (0.08, 0.50)
Vertical Impact Transient	0.30* (0.07, 0.50)	0.23 (-0.00, 0.44)	-0.22 (-0.43, 0.01)	-0.40* (-0.58, -0.18)	-0.32* (-0.51, -0.09)	0.13 (-0.11, 0.35)

*Denotes significantly different from zero at $p<0.05$. COM, centre of mass.

3.3.2 Regression models

The total amount of variance in the kinetic outcomes explained by the speed and selected kinematic variables ranged from 37-54% (Table 3.3). Regression coefficients are reported in Table 3.4 along with variance inflation factor (VIF). Excessive multicollinearity was not observed in any model (VIF<10). Residual analyses indicated that all data were consistent with the assumptions of linear regression.

3.3.2.1 Peak braking force

A model including speed, step length, foot strike angle, and heel to centre of mass distance explained 54% of variance in peak braking force (p=0.022). Greater baseline preferred

speed was associated with greater peak braking force. A longer step length and a greater (more rearfoot) foot strike angle were also associated with a greater peak braking force. When step length and foot strike angle were accounted for, a decreased heel to centre of mass distance was also associated with a greater peak braking force.

Table 3.3 Summary of regression models for predicting kinetic risk factors.

	R	R^2	Adjusted R^2	R^2 Change	p
Peak braking force					
Speed	0.67	0.45	0.44	0.45	<0.001
Speed + SL	0.71	0.50	0.49	0.05	0.009
Speed + SL + FSA	0.73	0.53	0.51	0.03	0.036
Speed + SL + FSA + HCOM	0.75	0.57	0.54	0.04	0.022
Average vertical loading rate					
Speed	0.42	0.18	0.17	0.18	<0.001
Speed + FSA	0.53	0.28	0.26	0.10	0.003
Speed + FSA + HCOM	0.63	0.40	0.37	0.12	0.001
Instantaneous vertical loading rate					
Speed	0.48	0.23	0.22	0.23	<0.001
Speed + FSA	0.57	0.32	0.30	0.09	0.004
Speed + FSA + HCOM	0.72	0.52	0.49	0.19	<0.001
Vertical impact transient					
Speed	0.30	0.09	0.08	0.09	0.012
Speed + HCOM	0.69	0.48	0.46	0.39	<0.001

Speed, baseline preferred speed; SL, step length; HFA, hip flexion angle at initial contact; HCOM, horizontal distance from heel to centre of mass; FSA, foot strike angle.

3.3.2.2 Average and instantaneous vertical loading rate

A model including speed, foot strike angle, and heel to centre of mass distance explained 37% of variance in average vertical loading rate (p=0.001) and 49% variance in instantaneous vertical loading rate (p<0.001). Greater baseline preferred speed was associated with both a higher average vertical loading rate and instantaneous vertical loading rate. A greater foot strike angle also predicted greater average vertical loading rate and instantaneous vertical loading rate. Similarly to peak braking force, after accounting for foot strike angle, average vertical loading

rate and instantaneous vertical loading rate were associated with a decreased heel to centre of mass distance.

3.3.2.3 Vertical impact transient

A model including speed and heel to centre of mass distance explained 46% of variance in vertical impact transient ($p<0.001$). After accounting for baseline preferred speed, a moderate amount of the variance in the magnitude of the vertical impact transient was explained by heel to centre of mass distance, with shorter distances associated with higher magnitudes.

Table 3.4 Unstandardized regression coefficients and variance inflation factors for variables in models.

	B +/- SE	VIF
Peak braking force (BW)		
Constant	-0.026 +/- 0.031	-
Speed	0.029 +/- 0.021	4.33
Step length	0.267 +/- 0.073	5.22
Foot strike angle	0.002 +/- 0.001	1.34
Heel to COM	-0.358 +/- 0.153	1.97
Average vertical loading rate (BW/s)		
Constant	-1.98 +/- 8.77	-
Speed	25.12 +/- 4.20	1.47
Foot strike angle	0.82 +/- 0.18	1.26
Heel to COM	-172.42 +/- 47.60	1.64
Instantaneous vertical loading rate (BW/s)		
Constant	-12.37 +/- 10.25	-
Speed	38.42 +/- 4.90	1.47
Foot strike angle	1.14 +/- 0.21	1.26
Heel to COM	-286.17 +/- 55.61	1.64
Vertical impact transient (BW)		
Constant	0.87+/- 0.16	-
Speed	0.49 +/- 0.08	1.32
Heel to COM	-5.81 +/- 0.82	1.32

B, unstandardized regression coefficient; SE, standard error; Speed, baseline preferred speed; COM, centre of mass; BW, body weight; s, second; VIF, variance inflation factor. The B values are expressed in units of kinetic outcome variable for every per unit increase in the predictor variables (speed, m/s; step length, m; foot strike angle, °; heel to centre of mass, m).

3.4 Discussion

The purpose of this study was to examine the contribution of several clinically useful kinematic variables to kinetic risk factors of running-related injury. We hypothesized that variables associated with overstriding would significantly contribute to the variance of our chosen kinetic outcomes. We also hypothesized that foot strike angle would be a significant contributor to all models.

Our findings indicate that a moderate amount (37-54%) of variance in kinetic outcomes associated with running-related injury (peak braking force, average vertical loading rate, instantaneous vertical loading rate, and vertical impact transient) may be explained by several discrete variables related to overstriding and foot strike posture. Although the relationship between some kinematic variables and kinetic outcomes has been described previously (61,62,114), we are unaware of any studies that have quantified the multivariable associations between purported kinetic risk factors for running-related injury and overstriding.

While speed was a significant contributor to all kinetic outcome models, it explained more variance in the peak braking force model than in the vertical ground reaction force models (8-22%). Running at a faster speed requires a relatively greater propulsive force. Therefore, given the equal and opposite relationship of braking and propulsive impulse during constant speed running on a treadmill, it is not surprising that speed was the greatest factor in explaining the variance in peak braking force. Our findings indicate that short of decreasing speed—an undesired intervention in most cases—peak braking force may also be reduced by shortening step length and transitioning away from a rearfoot strike pattern. Importantly, peak braking force was linked to a significantly higher risk of running-related injury in our prospective investigation in Chapter 2 (112).

After controlling for speed, step length, foot strike angle, and heel to centre of mass distance accounted for the remaining variance in the peak braking force model. Shank angle and hip flexion angle were not significant contributors to the explained variance when accounting for other variables. While a reduction in peak braking force from a decreased step length has not been reported previously, the likely mechanism for reducing peak braking force is via a reorientation of the ground reaction force vector, resulting in a less posteriorly oriented component. Using the unstandardized regression coefficient values from Table 3.4, we can determine the change in peak braking force per unit of each kinematic variable. For instance, a change of 1 unit (1 m) in step length is equal to a change of 0.267 BW in peak braking force. Therefore, after accounting for speed, to achieve a 0.04 BW reduction in peak braking force—a magnitude of one standard deviation in this sample (Table 3.1) and the difference between T1 and T3 in results from Chapter 2 (112)—would require a decrease in 0.148 m in step length (or 16.6%). Some studies have suggested a decrease of only 7.5-10% in step length is necessary to reduce vertical loading rates meaningfully (48,115). Therefore, the clinical feasibility of decreasing step length by the amount required in our study is questionable. Similarly, while a more forefoot strike angle corresponded with a decreased peak braking force, the clinical meaningfulness of this finding is debatable given that a decrease of 20° in foot strike angle would be required to decrease peak braking force by one standard deviation (0.04 BW), for a given speed and step length.

In our Pearson correlation analysis, heel to centre of mass distance was positively correlated with peak braking force. However, once speed, step length, and foot strike angle were accounted for, greater distances between the heel and centre of mass were actually associated with decreased braking forces. The direction of this relationship is in contrast to our hypothesis

and to findings by two other studies (48,61). Lieberman et al (61) posited that "the braking effects of 'overstriding' result from the position of the foot at landing relative to the body's centre of mass rather than to the position of the foot relative to the knee". Further, in a study that varied step frequency, Heiderscheit et al (48) reported that an increase in heel to centre of mass distance was associated with an increase in braking forces. When viewed in isolation, the positive relationship between heel to centre of mass distance and peak braking force reported in the previous two studies and seen in our Pearson correlation analysis is logical considering the increased posterior component of the ground reaction force vector with increased heel to centre of mass distance. However, in our regression analysis, when either speed or step length was added to the peak braking force model, heel to centre of mass distance was not a statistically significant contributor to the variance. Only after foot strike angle was added to the model with speed and step length did heel to centre of mass distance contribute a statistically significant share of the variance. Therefore, the contribution of heel to centre of mass distance to our model—once speed or step length was accounted for—was likely not clinically significant even though it attained statistical significance. Indeed, speed and step length made up almost 50% of the variance in this model, regardless of the order of entry. In other words, once these variables have been accounted for, the further information gained from heel to centre of mass distance may have statistical significance, but is not clinically meaningful. In further support of this interpretation, our regression analysis revealed that once speed, step length, and foot strike angle are accounted for, a 10 cm increase in heel to centre of mass distance would be required to decrease peak braking force by one standard deviation (0.04 BW).

Vertical loading rate—whether average vertical loading rate or instantaneous vertical loading rate—has been implicated as a risk factor for running-related injury in a number of

studies (18,20,24,28,29,31,104). The average vertical loading rate and instantaneous vertical loading rate models in this study consisted of the same subset of kinematic variables to explain 37% and 49% of the variance of those kinetic outcomes, respectively. After controlling for speed, foot strike angle and horizontal distance from heel to centre of mass accounted for the remaining variance in those models. A more rearfoot strike angle was associated with increased average vertical loading rate and instantaneous vertical loading rate. The significant contribution of foot strike angle to the variance in average vertical loading rate and instantaneous vertical loading rate fits with previous work (62). The lower vertical loading rates seen with a more forefoot strike pattern might be explained by a functionally longer lever at initial contact, producing a larger arc in the vertical trajectory of the centre of mass (79). Our results suggest that moving from a rearfoot strike to a more forefoot strike would be an appropriate gait retraining intervention to reduce vertical loading rate. Indeed, studies that have converted runners from a rearfoot to a forefoot strike pattern have shown a reduction in vertical loading rates (53,79). However, the regression coefficient in our analysis suggests that a decrease in foot strike angle of 14.5° would be necessary to decrease the average vertical loading rate by one standard deviation (11.9 BW/s). This may not be clinically feasible in many cases.

The Pearson correlation analysis demonstrated no significant relationship between heel to centre of mass distance and average vertical loading rate or instantaneous vertical loading rate. However, similar to the regression model for peak braking force, a decreased distance between the heel and centre of mass was associated with greater average vertical loading rate and instantaneous vertical loading rate once accounting for speed and foot strike angle. Again, when considering the increased vertical component of the ground reaction force vector when there is a decreased heel to centre of mass distance, a negative relationship between vertical loading rate

and heel to centre of mass distance is logical. Heel to centre of mass distance explains a greater amount of the variance in the average vertical loading rate and instantaneous vertical loading rate models than in the peak braking force model (12% and 19% versus 4%, respectively) after accounting for other variables. Again, the clinical practicality of this relationship is questionable given that a one standard deviation decrease in average vertical loading rate or instantaneous vertical loading rate would require an increase of 6.9 cm or 5.4 cm in heel to centre of mass distance for a given speed and foot strike angle, respectively.

The horizontal distance from the heel to the centre of mass accounted for a substantial amount (39%) of the variance in the vertical impact transient model after controlling for speed. No other kinematic variable contributed to the model. Once again, higher magnitudes were associated with a decreased heel to centre of mass distance. This is counter to findings by Heiderscheit et al (48) who found greater heel to centre of mass distance corresponded to increased frequency of vertical impact transient events, although magnitudes were not reported. Lieberman et al (61) reported that higher vertical impact transient magnitudes were associated with a more extended lower extremity and greater horizontal distance between ankle joint centre and knee joint centre. While the authors did not report the association between vertical impact transient magnitudes and horizontal distance between ankle joint centre and centre of mass (a measure more comparable to heel to centre of mass distance in our study), one would expect that the positive relationship would persist. Given the more vertically oriented ground reaction force vector at decreased heel to centre of mass distances, the negative relationship between vertical impact transient and heel to centre of mass distance in our Pearson correlation analysis and regression model is reasonable. The large contribution of the heel to centre of mass distance to the vertical impact transient model is supported by the more clinically meaningful regression

coefficient, which predicts that an increase of 4.2 cm in heel to centre of mass distance would result in a decrease of one standard deviation of vertical impact transient (0.25 BW), after accounting for speed.

Speed, step length, foot strike angle, and heel to centre of mass distance were significant contributors to our kinetic risk factor models. However, hip flexion and shank angle at initial contact did not contribute significantly to any of the models, indicating that these variables are of limited value relative to the other kinematic variables when estimating kinetic outcomes. While shank angle is often used clinically to estimate the degree of overstriding, it is also closely linked to the angle of knee flexion at initial contact, which has been shown to have no significant association with kinetic outcomes in two previous studies (61,62). Shank angle also had a moderate correlation with heel to centre of mass, likely due to the increased heel to centre of mass distance when the shank is angled forward from the vertical plane. Therefore, after accounting for heel to centre of mass distance in the models, shank angle likely did not provide any further information to explain the variance.

There are some limitations to this study. First, our sample includes females only. This was a conscious decision in recognition of the differences in biomechanical risk factors between males and females (20). However, Wille et al (62) found that sex did not directly affect the relationship between kinematic variables and kinetic outcomes. Therefore, our results may also be generalized to male runners. Second, our analysis was conducted on a treadmill and while kinetics have been shown to be similar between treadmill and overground running (90,91), some differences in kinematics have been documented (decreased step length and heel to centre of mass distance (110); more flexed knee at initial contact (110); more midfoot/forefoot strike (110,111)), which may limit the generalizability of the results to overground running. Finally,

only 18-39% of the variance in kinetic outcomes was accounted for by the variables of interest after controlling for speed. Therefore, there are likely other factors that influence vertical and anterior-posterior ground reaction force during the loading phase of running that were not included in this analysis.

3.5 Conclusions

Many experts suggest that reducing overstride is beneficial for reducing running-related injury risk (66). However, there is no consensus on what constitutes overstriding and there has been little evidence to support the importance of overstriding to running-related injury risk. While a definition of what constitutes an overstride is important, we suggest that the kinetic consequence of that overstride is more important. While a reduction in speed is one option for decreasing vertical and anterior-posterior loading, for runners wanting to maintain their preferred speed, several kinematic modifications may also achieve these outcomes. Our findings suggest that to reduce peak braking force, a focus on shortening step length and transitioning away from a rearfoot strike pattern are appropriate strategies. Further, to reduce vertical loading rates, we suggest that moving from a rearfoot strike to a more forefoot strike is an appropriate gait retraining intervention. Modifying shank angle and hip flexion angle do not appear to significantly contribute to the variance of these kinetic risk factors. Furthermore, heel to centre of mass distance—often cited as a measure of overstriding—appears to have little to contribute to a reduction in peak braking force once speed, step length, and foot strike are accounted for. While these results contribute to our understanding of the explained variance of kinetic risk factors of running-related injury, the clinical importance of our findings is debatable given the large changes in kinematic values required to effect clinically meaningful changes in kinetic

outcomes. Further prospective investigation into the strategies employed by runners to reduce anterior-posterior and vertical loading would be valuable.

Chapter 4: Real-time biofeedback of performance is an effective intervention to reduce braking forces associated with running-related injury

4.1 Introduction

Recreational running is one of the most accessible physical activities and has one of the highest participation rates of any sport worldwide (100). There are numerous recognized health benefits, but the prevalence of running-related injury is high. Up to 79% of runners are affected and approximately half of recreational distance runners will experience a running-related injury in any given year (10,101). Females are at greater risk of developing a running-related injury (10). Furthermore, a greater number of females entering running clinics also tend to be novice runners (5). Novice runners are particularly at risk as lack of running experience has been cited as one of the most important risk factors for running-related injury (4,6,102). Notably, a significant portion of those injured do not return to running (8). With differences in type and mechanism of running-related injury reported between males and females, it is important to study these populations in isolation (19-21).

There have been many proposed factors in the development of running-related injuries. While training error and an individual's anatomy are undoubtedly implicated, biomechanical factors are also believed to be involved (27). Among biomechanical variables, high magnitudes and rates of loading during the initial phase of stance have been associated with running-related injury (18,20,24,28-31). The magnitude of the vertical impact transient and the rate of vertical loading (average vertical loading rate or instantaneous vertical loading rate) have been the most commonly studied. Davis et al (18) reported that females with a prospectively high average vertical loading rate were at a greater risk of developing a running-related injury requiring

medical attention than those runners who had never sustained a running-related injury. However, this study did not find any differences in average vertical loading rate between injured and uninjured participants overall. In another prospective study, Bredeweg et al (20) reported that while baseline instantaneous vertical loading rate was prospectively higher in males who became injured, there was no difference between injured and uninjured females. In retrospective analyses, stress fractures and plantar fasciitis have also been linked to higher vertical loading rates, but causation cannot be inferred (28-30). Horizontal ground reaction force parameters may also be involved in running-related injury etiology. As shown in Chapter 2 (112), the anterior-posterior ground reaction force during loading demonstrated an increased risk of almost 800% (adjusted hazard ratio = 7.98) when comparing runners with a peak braking force>0.27 BW to lower peak braking force (<0.23) runners. Given this apparent link between peak braking forces and running-related injury risk, it is important to investigate methods to reduce these forces at impact.

Gait retraining has been suggested by some experts to be the most effective method to reduce loading parameters (66-68). A systematic review by our research group found that real-time kinetic or kinematic feedback was the most effective strategy for reducing vertical loading during running (71). This form of feedback may be effective because it allows the runner to develop their own movement strategy, rather than adhering to specific therapist-driven cues. For example, interventions that focus on cues to increase cadence or change to a forefoot strike may not be appropriate for all runners (high cadence or habitual forefoot strike runners, for instance) (68), so allowing the runner to develop their own strategy may be a better alternative than a 'one size fits all' approach (66). It has also been suggested that a patient-driven trial and error approach with gradual removal of feedback may result in an improvement in motor learning of

the modified gait pattern, rather than solely immediate improved performance (116). Indeed, motor learning principles play an important role in any gait retraining intervention and must be taken into account when designing the protocol (68). In addition, clinical feasibility should also be taken into consideration so that the results may be generalizable to this context (88).

There have been several examples of running gait retraining programs that have proven effective. Many of these studies have involved injured populations (53,72-74), but some have investigated the effects in healthy runners (22,75). Perhaps the most compelling of these studies to date is Chan et al's (22) recent large randomized controlled trial (n=320) investigating the effectiveness of a gait retraining program aimed at reducing vertical loading rates in novice runners. Participants in the intervention group received a two-week, eight-session lab-based gait retraining program. During the gait retraining intervention, participants were given real-time visual feedback of the vertical ground reaction force and were cued to "run softer" to reduce or eliminate the vertical impact peak. Participants in the control group ran for the same amount of time on the treadmill during their eight sessions, but received no feedback. At 12-month follow-up, the authors reported a reduction of 62% in running-related injury risk in the intervention group compared to the control group. This finding suggests that gait retraining programs should be considered an attractive option for reducing running-related injury risk among healthy individuals. Given the substantial impact that a gait retraining intervention might have on injury risk, it is important to test protocols to determine their effectiveness at achieving their targeted outcome, as well as determine the kinematic changes that are produced in order to guide clinical application (Chapter 3). A further consideration is the safety of such programs as there may be increased risk of injury when altering someone's natural running gait.

The purpose of this study was to determine whether a running gait retraining program

using real-time biofeedback of peak braking force could effectively reduce peak braking force magnitudes. Given the varied contribution of several kinematic and spatiotemporal parameters to higher vertical and anterior-posterior loading magnitude and rate (see Chapter 3), a secondary objective was to determine the self-selected kinematic strategies to achieve this reduction. We hypothesized that a 15-week gait retraining program would achieve a statistically significant ($p<0.05$) reduction in the target outcome (peak braking force) as well as secondary kinetic outcomes (average vertical loading rate, instantaneous vertical loading rate, and vertical impact transient). We also hypothesized that participants would preferentially choose to reduce their step length and foot strike angle at initial contact.

4.2 Methods

4.2.1 Participants

Female recreational runners between the ages of 18 and 60 were recruited from the local running community via flyers and social media posts. To obtain a novice running sample, inclusion was set to limit eligible participants to a history of no more than two half-marathons. Participants were required to have been running for at least three months and were excluded if they had experienced (1) a lower extremity injury in the previous three months, (2) any history of lower limb surgery, or (3) any current low back or lower extremity pain while running. Participants in the previous cohort (those involved in the studies comprising Chapters 2 and 3) were excluded from participating in this study. Written consent was obtained from all participants, and ethics approval was granted from the institutional Clinical Research Ethics Board. This protocol was registered on ClinicalTrials.gov (NCT03302975).

Interested participants were initially screened by phone or email for inclusion and

exclusion criteria and eligible individuals were then invited to undergo an initial biomechanical screen. Eligible participants attended the laboratory for a biomechanical running screening on an instrumented treadmill (Treadmetrix LLC, Park City, UT) in their usual running shoes and at a self-selected speed representative of a moderate intensity run (Borg Rating of Perceived Exertion = 13, indicative of "somewhat hard") (93). Six reflective markers (one heel triad per foot) were affixed to the heels to identify left and right ground contacts. The mean peak braking force across three captures of 15 seconds (n=30 stance phases per foot) was calculated.

In a previous study (see Chapter 2 (112)), runners with a peak braking force>0.27 BW were injured at five times the rate of those between 0.23-0.27 BW and eight times the rate of those in <0.23 BW, when adjusted for age and speed. As the ultimate goal of any gait retraining program is to reduce the level of injury risk, a pre-determined criterion of >0.27 BW was selected as the threshold. The limb with the higher mean peak braking force was chosen as the study limb. Therefore, only individuals who exhibited a peak braking force of >0.27 in one of their limbs at this initial biomechanical screen were deemed eligible for the study.

Sample size calculations were conducted in G*Power 3.1.9.3. Sample size for our study was calculated to detect a clinically meaningful reduction of 0.04 BW (one SD based on our results from Chapter 2 (112)) for our primary outcome (peak braking force). To obtain 80% power to detect significant ($p<0.05$) differences in peak braking force from baseline to follow-up measurements, we determined that 13 participants were required. Taking into account an attrition rate of 20% based on our previous study (Chapter 2) (112) and another using a similar population (12), we aimed to recruit 16 participants for this study.

4.2.2 Baseline assessment

Individuals who met the initial biomechanical screening criterion were invited to the laboratory for a baseline (Week 0) testing session where a detailed training and injury questionnaire was administered. Three-dimensional kinematic and kinetic data were collected and processed as outlined in section 1.6.1. Participants were provided no instructions pertaining to running mechanics during the baseline testing session. A modified marker set for the lower extremity, consisting of 16 static/calibration markers (anterior superior iliac spines, greater trochanters, medial/lateral femoral condyles, medial/lateral malleoli, and first and fifth metatarsal heads) and 26 tracking markers (posterior superior iliac spines, iliac crests, clusters of four on the thigh and shank, and a triad on the heel) were affixed to each participant prior to testing (Figure 4.1), and a static calibration trial was initially collected to form a musculoskeletal model (see section 1.6.2). For the purpose of obtaining a proxy for heel to centre of mass distance in the absence of a full body marker set, a virtual marker was created at the midpoint between posterior superior iliac spine markers in order to calculate the horizontal distance between the heel and sacrum at initial contact. A sacral marker has been shown to be a reliable proxy for centre of mass in the sagittal plane during gait (117).

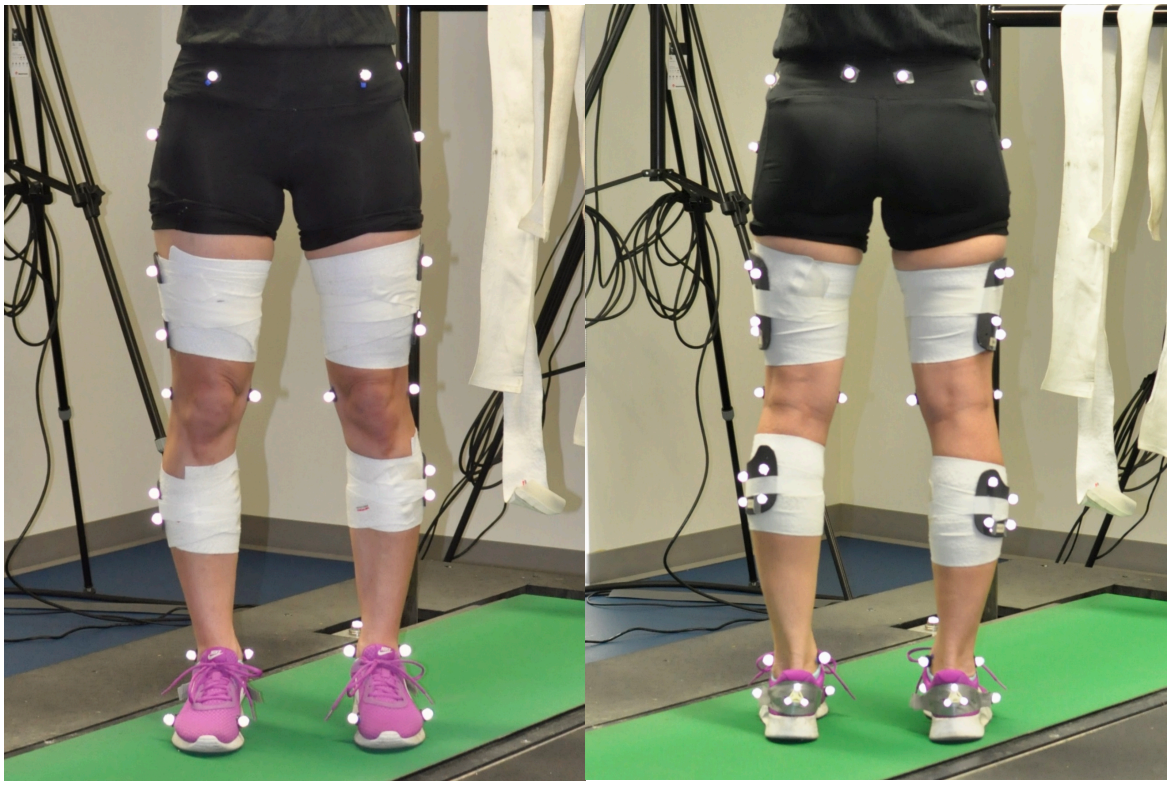


Figure 4.1 Marker positions for static trial.
For bilateral analysis, 16 static/calibration markers and 26 tracking markers (total = 42) were affixed to each subject.

Our primary kinetic outcome of interest was peak braking force, based on our previous study that showed increased risk of injury with higher values (Chapter 2 (112)). Peak braking force was defined as the maximum posterior force observed from initial contact to 50% of stance. Secondary kinetic outcomes were selected based on their inclusion in the running-related injury literature and consisted of vertical impact transient (27,28), average vertical loading rate (24,28), and instantaneous vertical loading rate (27-29), and were calculated as described in section 2.2.5. Kinematic outcomes included step length; step frequency; the horizontal distance from the heel to the sacrum; shank angle at initial contact; and foot strike angle. Heel to sacrum distance was used as a surrogate for the horizontal distance between the heel and the centre of mass because we did not use a full-body marker set and could, therefore, not precisely calculate

centre of mass. Kinematic variables were selected due to their contribution to higher peak braking force based on previous studies (48,61) and our findings from Chapter 3. The potential for use of these kinematic variables to cue lower peak braking force during running retraining in a clinical setting was also taken into consideration for variable selection.

4.2.3 15-week half-marathon training intervention

At the baseline session (Week 0), participants were given a structured 15-week home-based half-marathon training program, incorporating four runs per week—two speed/hill sessions, one easy recovery run, and one long run—identical to the one presented in Chapter 2 (see section 1.6.3 and Appendix A). During weeks where there was a lab-based gait retraining session (see section 4.2.4), this took the place of the easy recovery run. The program was supervised by a sport physiotherapist with 14 years of experience. Prescribed weekly running volume increased throughout the training program from approximately 3 hours of running in Week 1 to 4.75 hours by Week 14, in preparation for a half-marathon race at the end of Week 15. Throughout the training program, participants completed a weekly online questionnaire (see Appendix B) to record: any pain and its location; the number and reason for missed training days; time run per week (hours) and workouts completed; and any general comments regarding their training or pain.

4.2.4 Gait retraining sessions

Participants commenced the gait retraining portion of the intervention in Week 1. This program consisted of eight lab-based sessions at Weeks 1, 2, 4, 6, 8, 10, 12, and 14 of a half-marathon training program (see section 4.2.3 above), with sessions starting at 15 minutes of

continuous running in Week 1 and increasing to 30 minutes by Week 10 (Figure 4.2).

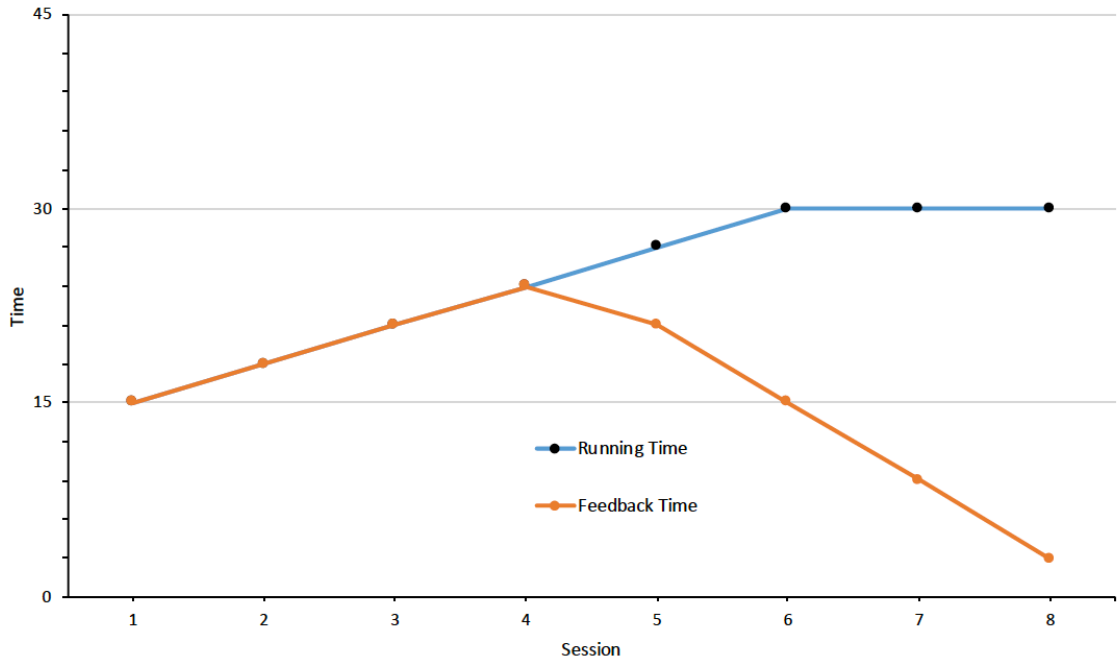


Figure 4.2 Total running time and time with feedback during the eight lab-based training sessions. For the first four sessions, participants received feedback 100% of the time. By session 8, feedback was only provided 10% of the total time.

Gait retraining during the lab-based sessions was facilitated by real-time biofeedback of the anterior-posterior (braking) ground reaction force using Visual 3D Server (C-Motion Inc., Germantown, USA). Kinetic data was streamed to a monitor positioned directly in front of the treadmill (Figure 4.3). Participants were instructed to attempt to keep the peaks on a rolling graph below a green line that had a value of 0.245 BW (the mean peak braking force from the study in Chapter 2 (112)), with the encouragement that lower was better (Figure 4.4). No other cues were given so that participants could develop their own strategies to lower peak braking force. To promote motor learning, a faded feedback design was used with removal of biofeedback (monitor turned off) commencing at session 5 (Figure 4.2) (72-74). Self-reported

difficulty in achieving the target zone was recorded at each training session using an 11-point numerical rating scale (NRS) with terminal descriptors of 0 = “no difficulty” and 10 = “unable to perform”). Participants were instructed to maintain the modifications outside the lab-based training sessions whilst running in the community.

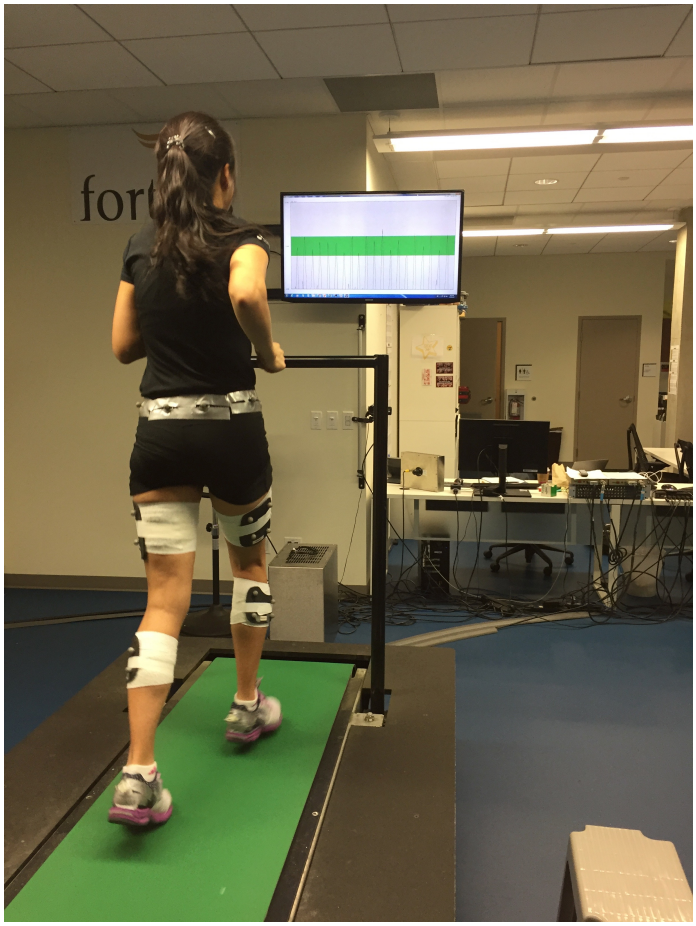


Figure 4.3 Experimental setup during gait retraining sessions.
A monitor was positioned in front of the participant and real-time braking force was displayed. Participants were instructed to keep the peaks on a rolling graph below a green line that had an upper value of 0.245 BW.

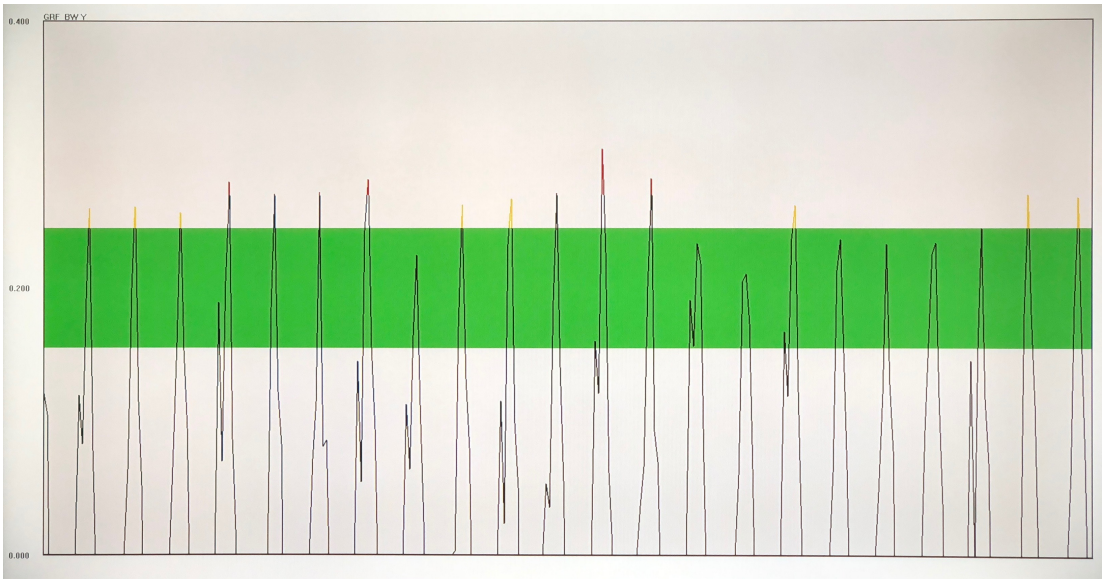


Figure 4.4 Real-time biofeedback display during gait retraining sessions.
A monitor was positioned in front of the participant and real-time braking force was displayed. Participants were instructed to keep the peaks on a rolling graph below a green line that had an upper value of 0.245 BW.

4.2.5 Adherence, difficulty, and adverse events

Adherence to the training program was assessed as the total number of lab-based training sessions attended for each participant. Compliance with the prescribed half-marathon training program was obtained from weekly online questionnaire responses completed by participants detailing the daily amount of running for the duration of the study, and weekly totals (in hours) were calculated. Additionally, an 11-point NRS (0 = “not confident at all”, 10 = very confident) in the weekly questionnaire was used to assess confidence in the ability of participants to maintain the modified gait pattern whilst running in the community. Finally, concurrent treatments and adverse events were assessed using open-ended questions in the weekly questionnaire. For the purpose of analysis, adverse events were defined as those lasting longer than two weeks in duration or requiring additional treatment.

4.2.6 Follow-up assessment

Participants returned to the lab in Week 15 for follow-up testing. Markers were applied and biomechanical data were collected in the same manner as at baseline testing. Participants ran at their baseline preferred speed. After an initial warm-up period, participants were instructed to "run naturally" while the first three consecutive captures of data were collected (follow-up natural gait; NAT). They were then asked to run with their new 'modified gait' (follow-up modified gait; MOD) while three further consecutive captures of data were collected.

4.2.7 Statistical analysis

This was an interventional repeated measures study design to determine whether a gait retraining program is able to change kinetic risk factors of running-related injury in a novice recreational running population. The primary outcome was peak braking force, and the primary endpoint was the natural gait pattern at follow-up assessment (NAT). All other biomechanical and clinical outcomes were considered secondary. Within-subject comparisons using repeated measures analysis of variance (ANOVA) were used to compare the effect of the gait retraining program on primary and secondary outcomes, and effect sizes (ES) were reported. Post hoc 2-tailed comparisons were conducted using a criterion $p=0.05$, while a statistical trend was defined as being $0.10>p>0.05$. Post hoc comparisons were conducted from baseline to NAT. Exploratory comparisons were then made between baseline and MOD. A large effect size was determined as > 0.80, moderate >0.40, and small < 0.40 (118). All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, USA).

4.3 Results

Between July and September 2017, 183 individuals underwent eligibility screening (Figure 4.5). Forty-six individuals met inclusion criteria and attended the laboratory for biomechanical screening. Of these, 16 met the biomechanical screening criterion of peak braking force>0.27 BW and underwent baseline testing. Twelve participants completed the 15-week half-marathon training program and follow-up biomechanical gait assessment (Table 4.1). Reasons for loss-to-follow-up included: acute back injury unrelated to running (n=2), acute illness (n=1), and pregnancy (n=1).

Table 4.1 Demographics of participants.
Data are reported as mean +/- SD for all variables.

	Baseline (n=16)	Follow-up (n=12)
Age (years)	39.2 +/- 8.7	39.4 +/- 9.1
Height (m)	1.70 +/- 0.06	1.70 +/- 0.05
Body mass (kg)	64.8 +/- 7.3	63.7 +/- 5.9
Body mass index (kg/m^2)	22.6 +/- 2.3	22.2 +/- 1.7
Running experience (years)	11.3 +/- 7.9	9.6 +/- 8.3
Prior weekly volume (km)	14.0 +/- 9.5	14.5 +/- 9.1
Baseline preferred speed (m/s)	2.57 +/- 0.16	2.56 +/- 0.18

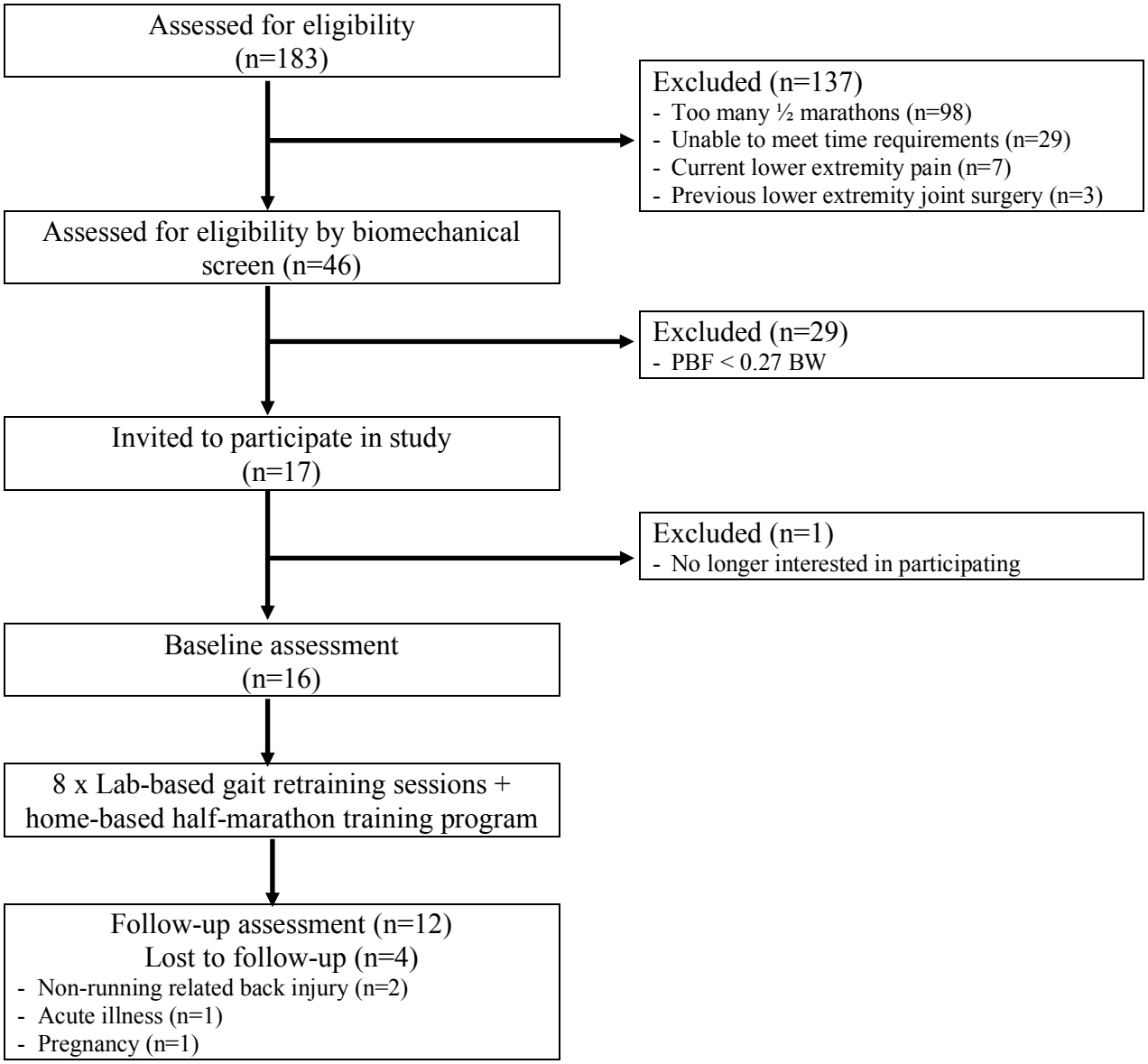


Figure 4.5 Flow of participants through study.

When comparing the natural gait at follow-up to baseline (Table 4.2), there was an average reduction of 15% in peak braking force (p=0.001). Though not statistically significant, average vertical loading rate and instantaneous vertical loading rate were also reduced by 18% (p=0.076) and 19% (p=0.064), respectively. Kinematic analysis of baseline and follow-up natural gaits revealed an increase of 7% in step frequency (p=0.024) and decrease of 6% in step length (p=0.020). There was also a non-statistically significant trend (p=0.076) toward a 1° reduction in the shank angle at initial contact (to a more vertical shank).

Table 4.2 Kinetic and kinematic outcomes of participants (n=12) at baseline and follow-up (natural gait). Data are reported as mean +/- SD for all variables.

	Baseline	Follow-up (natural gait)	Mean difference (95% CI)	p	Effect Size
Kinetic outcomes					
PBF (BW)	0.284 +/- 0.035	0.241 +/- 0.021	-0.043 (-0.065, -0.020)	0.001	0.62
VIT (BW)	1.56 +/- 0.15	1.46 +/- 0.25	-0.11 (-0.29, 0.08)	0.233	0.13
AVLR (BW/s)	43.96 +/- 11.64	36.05 +/- 7.45	-7.91 (-16.79, 0.98)	0.076	0.26
IVLR (BW/s)	55.49 +/- 15.51	44.98 +/- 10.10	-10.51 (-21.76, 0.74)	0.064	0.28
Kinematic outcomes					
Horizontal distance from heel to	24.2 +/- 2.4	24.5 +/- 3.4	0.2 (-1.9, 1.5)	0.778	0.01
Shank angle (°)	6.6 +/- 2.5	5.6 +/- 2.9	-1.0 (-2.2, 0.1)	0.076	0.26
Foot strike angle (°)	6.3 +/- 6.1	6.1 +/- 5.8	-0.2 (-4.0, 3.5)	0.886	0.00
Step frequency (steps/min)	170.6 +/- 9.2	181.9 +/- 16.8	11.3 (1.8, 20.9)	0.024	0.38
Step length (cm)	90.6 +/- 6.8	85.2 +/- 5.1	-5.5 (-9.9, -1.0)	0.020	0.40

PBF, peak braking force; VIT, vertical impact transient; AVLR, average vertical loading rate; IVLR, instantaneous vertical loading rate; BW, body weights; s, second. Foot strike angle measured from the horizontal with a positive angle indicating a more rearfoot strike. Shank angle measured from the vertical with a positive angle indicating that the ankle is anterior to the knee.

Comparing follow-up modified gait kinetic data to baseline (Table 4.3), there was an average 18% reduction (p=0.001) in peak braking force. There was also an associated 24% reduction in average vertical loading rate (p=0.025) and instantaneous vertical loading rate

(p=0.028). Analysis of the kinematic data revealed a 9% increase in step frequency (p=0.021) and an 8% decrease in step length (p=0.016).

Table 4.3 Kinetic and kinematic outcomes of participants (n=12) at baseline and follow-up (modified gait). Data are reported as mean +/- SD for all variables.

	Baseline	Follow-up (modified gait)	Mean difference (95% CI)	p	Effect Size
Kinetic outcomes					
PBF (BW)	0.28 +/- 0.04	0.23 +/- 0.02	-0.05 (-0.08, -0.03)	0.001	0.66
VIT (BW)	1.56 +/- 0.15	1.43 +/- 0.27	-0.14 (-0.32, 0.05)	0.126	0.20
AVLR (BW/s)	43.96 +/- 11.64	33.46 +/- 7.86	-10.49 (-19.41, -1.58)	0.025	0.38
IVLR (BW/s)	55.49 +/- 15.51	42.36 +/- 10.78	-13.13 (-24.59, -1.68)	0.028	0.37
Kinematic outcomes					
Horizontal distance from heel	24.2 +/- 2.4	24.9 +/- 4.1	0.7 (-1.4, 2.8)	0.503	0.04
Shank angle (°)	6.6 +/- 2.5	5.8 +/- 3.1	-0.8 (-2.2, 0.6)	0.255	0.12
Foot strike angle (°)	6.3 +/- 6.1	5.1 +/- 5.8	-1.2 (-5.2, 2.8)	0.518	0.04
Step frequency (steps/min)	170.6 +/- 9.2	185.8 +/- 21.5	15.2 (2.8, 27.6)	0.021	0.40
Step length (cm)	90.6 +/- 6.8	83.7 +/- 6.1	-7.0 (-12.3, -1.6)	0.016	0.43

PBF, peak braking force; VIT, vertical impact transient; AVLR, average vertical loading rate; IVLR, instantaneous vertical loading rate; BW, body weights; s, second. Foot strike angle measured from the horizontal with a positive angle indicating a more rearfoot strike. Shank angle measured from the vertical with a positive angle indicating that the ankle is anterior to the knee.

When training sessions were analyzed on an individual level, it was noted that peak braking force did not change appreciably between the first and the last session (Figure 4.6). In other words, the participants were able to successfully produce the modified gait pattern necessary to lower peak braking force from the initial training session. Self-reported difficulty in achieving the target threshold of peak braking force for a given training session also did not change significantly from the first (4.8 +/- 2.4) to the last session (4.6 +/- 1.3). However, given that the running time increased (from 15 to 30 minutes) and feedback time decreased (from 100% to 10%) over the course of the eight sessions, it is possible that participants gained an ability to sustain the modified pattern for longer and with less feedback as a result of the extra training sessions. In further support of this is the confidence in the participants' perceived ability

to achieve the modified gait pattern, which improved from 5.9 +/- 1.6 out of 10 in Week 1 to 7.5 +/- 1.3 in Week 15.

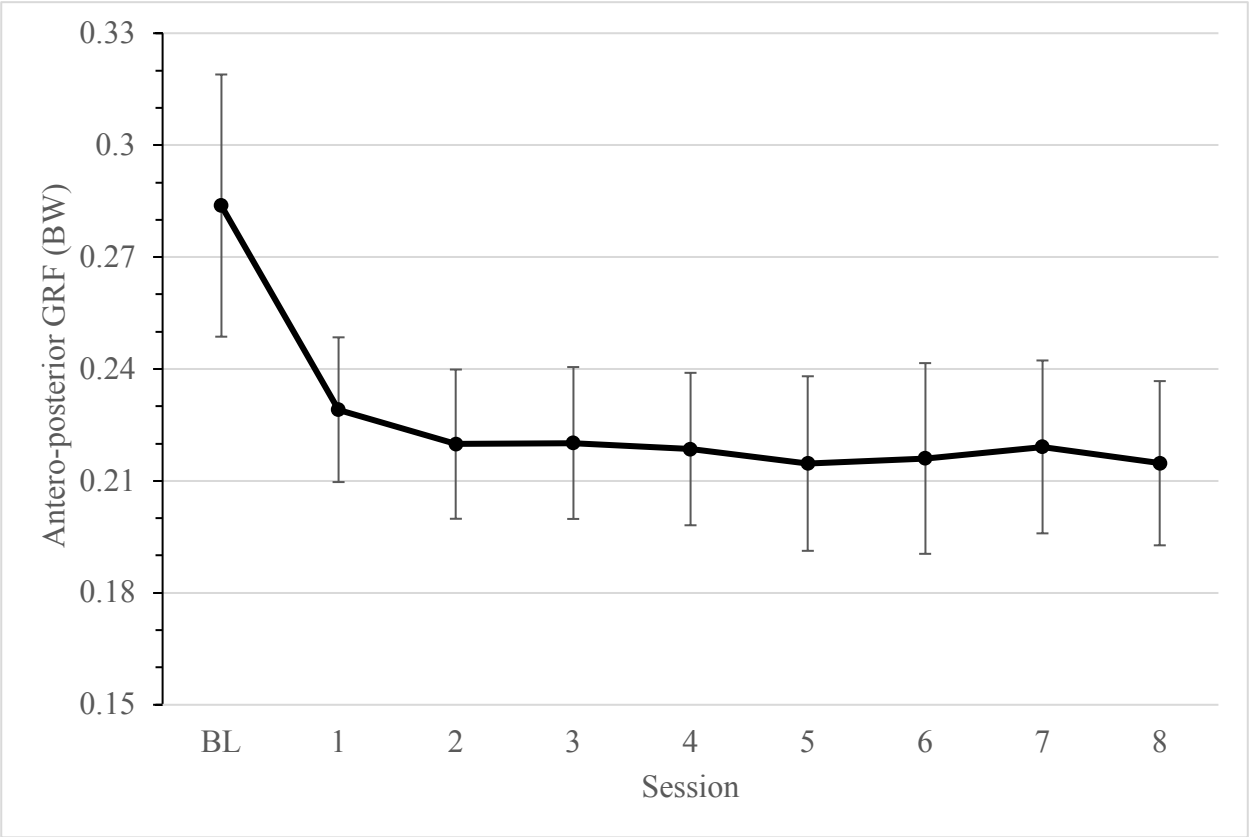


Figure 4.6 Peak braking force during lab-based sessions.
Error bars show SE. GRF, ground reaction force; BW, body weight; BL, baseline.

Attendance at the lab-based training sessions was almost perfect. All participants except one attended all eight sessions. Compliance with the half-marathon training program was also good. Participants completed a median of 52 out of 60 runs (IQR=50.5, 56.5) over the duration of the half-marathon training program, for a mean of 2.88 +/- 0.40 hours of running per week.

Pain was low throughout all training sessions (0.7 +/- 0.3 out of 10). There were no self-reported adverse events or concurrent treatments reported over the course of the half-marathon

training program. However, one lab-based training session (Session 8) was terminated at 24 minutes due to bilateral shin pain.

4.4 Discussion

This study is the first, to our knowledge, to assess the biomechanical effects of a gait retraining program to reduce peak braking force in recreational runners. While previous studies have utilized real-time biofeedback of kinetic parameters to reduce vertical loading parameters (22,25,53), ours used real-time biofeedback of braking forces as an intervention. Female recreational runners with high baseline peak braking force were targeted because of their increased risk of developing a running-related injury, as demonstrated in Chapter 2 (112). Our findings indicate that recreational runners can reduce their peak braking force over the course of an eight-session real-time biofeedback gait retraining program. Furthermore, this modified pattern can be learned to the extent that it is incorporated into an individual's natural gait pattern.

On average, the retraining program produced a 15% reduction in our primary outcome variable of peak braking force. Based on our a priori inclusion criteria, the average baseline magnitude of peak braking force (0.28 BW) would have placed our participants in the highest tertile in our study detailed in Chapter 2 (112). Follow-up magnitudes of peak braking force averaged 0.24 BW, which would have placed our participants in the middle tertile (and five times less likely to develop a running-related injury based on the previously mentioned study). There are no other prospective studies that have investigated the relationship between peak braking force and running-related injury, but based on our results in Chapter 2, a reduction of peak braking force of this magnitude is likely to be clinically meaningful.

Importantly, average vertical loading rate and instantaneous vertical loading rate were also reduced by 18% and 19%, respectively, from baseline to follow-up, suggesting that the strategies employed to reduce peak braking force also have the added benefit of reducing these parameters. The magnitude of these reductions is on par with the differences for average vertical loading rate (~22%) and instantaneous vertical loading rate (~17%) between groups (never injured versus injuries that required medical attention) in the prospective study by Davis et al (18). Esculier et al (75), in their randomized controlled trial, also reported similar reductions (~26%) in average vertical loading rate in their gait retraining group. Participants in that study received instructions to increase their step frequency between 7.5-10% and to "run softer" with a forefoot strike pattern. Furthermore, in retrospective studies examining the association between vertical loading rate and tibial stress fractures, the difference in vertical loading rate between injured and controls was, on average, 12% (31). Therefore, an indirect benefit of the current gait retraining program may be to lower injury risk by way of reducing vertical loading rate.

Kinematic analysis revealed that participants reduced their peak braking force magnitude by shortening their step length and increasing their step frequency. On average, participants increased their step frequency by 7%, which is consistent with the 5-10% reported by previous intervention studies (48,115). Due to differences in baseline values, not all participants increased their step frequency by this degree. When participants were asked to report their strategy for the modified gait pattern, all but three stated either "increasing step frequency" or "taking shorter steps." There was no difference in the heel to sacrum distance (a surrogate measure for heel to centre of mass distance). This is in contrast with previous studies that showed a relationship between greater heel to centre of mass distance and increased braking forces (48,61). However, as we posited in Chapter 3, it might be that there is no further benefit to reducing this distance

once step length has been reduced. Furthermore, there was no difference in shank angle between baseline and follow-up, meaning that a more vertical orientation of the angle of the shank at initial contact is not necessary to produce a reduction in peak braking force. This result is in agreement with findings in Chapter 3 in which the angle of the shank did not contribute to the explained variance of peak braking force. Two previous studies that examined knee flexion angle at initial contact—a related measure to shank angle—also determined that knee flexion angle is not an important determinant of braking force (61,62). Importantly, shank angle is often used clinically to estimate the degree of overstriding, but the above findings suggest that shank angle may not be indicative of this parameter.

Additionally, there was no difference in foot strike angle between baseline and follow-up. This is in contrast to our findings in Chapter 3, which showed that a more forefoot strike angle was related to lower peak braking force and vertical loading rates. Results from Chapter 3 indicate that to achieve the reduction in peak braking force that was seen in this study, an average decrease in foot strike angle of almost 20° (>3 SD) would have been necessary. However, this was after accounting for speed and step length. Interestingly, in a study examining the independent effect of foot strike pattern and step length on kinetic parameters, Bowersock et al (119) reported that decreasing step length, but not changing foot strike pattern, reduced braking forces.

The lack of change in foot strike angle is in contrast with two previous studies that have reported lower vertical ground reaction force measures (vertical impact transient, average vertical loading rate, and instantaneous vertical loading rate) in runners with lower foot strike angles (53,82). However, unlike in those studies, we chose to include all foot strike types in our study sample, potentially contributing to a floor effect on decreasing foot strike angle below a

certain level. When individual participant data were reviewed, it was noted that all participants who had a foot strike angle >10° (n=3) reduced their foot strike angle at follow-up, suggestive of a more forefoot strike, but there was no clear pattern below this angle. In summary, this finding provides evidence that rearfoot strike patterns must not necessarily change to midfoot or forefoot to reduce vertical and anterior-posterior loading parameters, except possibly in the case of more pronounced rearfoot strikes (foot strike angle >10°).

The gait retraining program in this study was designed to follow a faded feedback paradigm over multiple sessions to improve learning and retention of the modified gait pattern (68,85). Participants were provided with real-time, externally focused feedback of braking force without further instruction on how to achieve a reduction in this parameter (120,121) and the amount of this feedback was then reduced from sessions five to eight (Figure 4.2). This approach also allowed us to achieve our secondary objective of determining the kinematic strategies used by participants to reduce peak braking force. In a recent editorial on optimizing gait retraining, Davis (68) advised that evidence should be provided regarding whether the gait pattern has been 'retrained' or whether the runner has simply been able to reproduce the modified pattern when tested. Therefore, we assessed the participant's natural gait pattern at follow-up before asking them to run with the modified gait pattern. Our findings indicate that the gait retraining program was effective at altering the natural gait among our participants, with participants achieving significant reduction in peak braking force in this condition.

There were no self-reported adverse events either during the lab-based training sessions or during the half-marathon training program. There were some reports of soreness in the knees and tightness in the calves by some participants throughout the middle of the 15-week program. However, none of these complaints met the a priori criteria of lasting longer than two weeks in

duration or requiring additional treatment, and average pain during the lab-based training sessions was less than 1/10. The lack of adverse events indicates that not only is this intervention effective at reducing peak braking force, but that it is also potentially safe. However, we would advise accompanying the program with an ankle and knee strength program to minimize risk of injury.

This study is not without limitations. First, this study was designed to be preliminary in nature, in order to test whether individuals could be retrained to reduce their peak braking force. Because of the absence of a control group, we cannot suggest that this intervention is superior to a half-marathon training program alone. However, it is unlikely that the biomechanical changes seen would have occurred without the retraining program (122). A randomized controlled trial is warranted to compare this type of gait retraining program to one that could be carried out in a clinical environment using kinematic cues. Second, this study only followed participants up to the end of the 15-week half-marathon training program and did not evaluate participants after the training ended. As such, the long-term retention of this modified gait pattern is unknown. Third, given that our participants consisted of novice female runners, we can only generalize our findings to this group. However, as long as the principles of this training protocol are adhered to, we see no reason that males and trained runners could not see the same benefits. Finally, it is unknown whether the gait modifications observed in the laboratory were transferred to the community. Given the increasing availability and capability of wearable devices, data should be collected in the community to determine whether transference from the lab is occurring (123,124).

4.5 Conclusions

The gait retraining program in this study significantly reduced the peak braking force, as well as vertical loading rates associated with running-related injury. This was achieved through a combination of increased step frequency and decreased step length. Furthermore, the modified gait pattern was safe and incorporated into the runners' natural gait pattern by the completion of the gait retraining program. Based on these results, the outlined gait retraining program could provide a powerful injury prevention strategy for recreational runners. Further investigation into a clinical application of this program is warranted to enable wider use.

Chapter 5: General discussion

5.1 Overview

The results of this thesis provide a greater understanding of, and treatment for, the biomechanical risk factors of running-related injury by comparing the hazard ratios of kinetic parameters and identifying their kinematic correlates. Specifically, we examined the risk of running with higher peak braking forces and assessed the ability of a gait retraining program to reduce these forces. Accordingly, this thesis advances the understanding of kinetic risk factors of running-related injuries and potential strategies to reduce these risks.

In Chapter 2 we examined six kinetic variables and determined the risk of developing a running-related injury between high, medium, and low tertiles. A runner with a higher peak braking force (T3) was found to have five to eight times the risk of developing a running-related injury over the course of a 15-week training program when compared to medium (T2) or lower (T1) peak braking force, respectively. Contrary to some previous studies, a higher vertical loading rate (average vertical loading rate or instantaneous vertical loading rate) was not found to increase the risk of developing injury. In Chapter 3 we explored the kinematic correlates of four of the kinetic risk factors from Chapter 2 to investigate the relationship between lower extremity posture and vertical and anterior-posterior loading. The kinematic variables chosen were clinically relevant parameters often used to describe overstriding. This study found that after accounting for speed, step length and foot strike angle were important determinants of peak braking force, and that foot strike angle and distance from the heel to the centre of mass best explained average vertical loading rate and instantaneous vertical loading rate.

The results from Chapters 2 and 3 informed Chapter 4, which investigated the feasibility and efficacy of retraining runners who had higher peak braking force. Real-time biofeedback of braking forces was provided to participants over eight lab-based sessions and participants were allowed to develop their own retraining strategies based on this feedback. All participants were able to reduce their peak braking force as a result of the gait retraining program. The primary strategy employed was a reduction in step length/increase in step frequency. Interestingly, other parameters often identified as clinically meaningful—such as the heel to centre of mass distance, foot strike pattern, or the angle of the shank at initial contact—were no different after the gait retraining program, suggesting that they may not be clinically useful after changing step length/rate.

Taken together, these studies offer new insight into injury risk factors in running and inform a clinical paradigm for reducing these risk factors. Further, the results of these studies provide avenues for future research and strategies to help reduce injury risk in runners.

5.2 Kinetic risk factors of running-related injuries and their kinematic correlates

Kinetic risk factors have been linked to running-related injury in a number of previous studies (24,29,31). Recent prospective investigations have reported conflicting results on the role of average vertical loading rate and instantaneous vertical loading rate in the development of injury (18,20,26), although gait retraining to reduce vertical loading rate has shown promise for decreasing injury risk (22). Peak braking force, on the other hand, has never been prospectively investigated as a risk factor of running-related injury. Therefore, in addition to clarifying the role of average vertical loading rate and instantaneous vertical loading rate, we sought to explore the risk of higher peak braking force on running-related injuries in Chapter 2.

Our results demonstrated a non-statistically significant trend toward greater injury risk among higher (T1) average vertical loading rate when compared to lower (T3) average vertical loading rate runners, adding to the debate on the importance of vertical loading rate on running-related injury. Interestingly though, a higher peak braking force was found to significantly increase the risk of developing a running-related injury. This is the first prospective study to demonstrate this link. It is known that bones do not withstand shear (horizontal) forces as well as they withstand compressive (vertical) forces, despite the magnitudes being several times greater for the latter (40,41). Although shear forces are relatively small, they can become substantial in long bones (such as the tibia or femur) that are subjected to torsion (41). Torsional loading causes shear stresses along and transverse to the long axis of the bone, which can lead to the development of stress fractures (41). Of note, the most common injury in our Study 1 cohort was medial tibial stress syndrome. Furthermore, five of the six incidences of medial tibial stress syndrome occurred in the highest tertile of peak braking force. Increased shear forces have been proposed to play a role in the development of some soft tissue injuries such medial stress syndrome (44). It has been suggested that medial tibial stress syndrome may actually be classified into four different entities: stress fracture (type 1a), stress microfracture/diffuse stress reaction in the tibia (type 1b), chronic periostalgia (type 2), and chronic exertional compartment syndrome of the deep or superficial compartment (type 3) (125). Type 1b (stress reaction) and type 2 (chronic periostalgia) may be due to the same pathogenic process. A recent investigation reported that medial tibial stress syndrome was not related to signs of a posteromedial tibial periostitis, but that bony overload (stress reaction) could be more likely (44). If the latter is true, then the same pathogenic processes—of which increased shear forces is one proposed mechanism—may be responsible for both medial tibial stress syndrome and tibial stress fracture.

This may be one mechanism that higher peak braking forces may have contributed to increased injury risk in our cohort.

Shear loads may also be difficult for muscle forces to attenuate given that most muscles in the lower extremities are oriented in a way to either produce or absorb forces in an axial direction. As a result, shear forces may be more demanding on the soft tissues of the lower extremities and, therefore, may be more likely to cause breakdown of these tissues over repetitive loading cycles. Shear forces applied to the foot and lower leg may also increase the risk of certain injuries to these regions (42). Specifically, the tibia (37) and metatarsals (43) have been suggested to be less able to withstand horizontal than vertical loads.

Another consideration is that our sample consisted of novice female recreational runners. Novice runners may be at increased risk of injury compared to experienced runners due to a reduced ability to withstand higher loading rates, and this vulnerability may be more apparent in the braking component than the vertical component.

The posture of the lower extremity at initial contact and during the loading phase has been reported to influence the magnitude and rate of loading (48,61,62). Although there have been previous investigations into kinematic correlates of kinetic risk factors of running-related injury (61,62,114), none have examined the multivariable relationship between kinematic parameters clinically related to overstriding and the potential kinetic consequence of overstriding (e.g. higher peak braking force). While many experts agree that reducing overstride is beneficial for reducing running-related injury risk, there is no consensus on what constitutes overstriding and there has been little evidence to support the importance of overstriding to running-related injury risk (66). While a definition of what constitutes an overstride (e.g. increased heel to centre of mass distance, greater shank angle, etc.) is important, we suggest that more important is the

consequence of that overstride (e.g. increased peak braking force and vertical loading rate). The link between greater step lengths and higher peak braking force (as seen in the results from Chapters 3 and 4) could also explain some of the injury findings. Edwards et al (50) suggested that a 10% reduction in preferred step length reduces the risk of developing a tibial stress fracture. If medial tibial stress syndrome and tibial stress fractures are borne of similar pathogenesis, then the increased step length associated with higher peak braking forces could be the kinematic culprit behind this condition.

The results from Chapter 3 demonstrate that a moderate amount (37-54%) of variance in kinetic outcomes associated with running-related injury (average vertical loading rate, instantaneous vertical loading rate, peak braking force, and vertical impact transient) can be explained by several discrete variables related to overstriding. Our findings suggest that to reduce peak braking force, a focus on shortening step length and transitioning away from a rearfoot strike pattern are appropriate strategies. Shortening step length has the effect of reorienting the ground reaction force vector less posteriorly, thus decreasing the braking force. After accounting for speed and step length, a decrease in foot strike angle was also associated with a lower peak braking force. Interestingly, unlike in Boyer et al (54), who found that forefoot strike runners had a peak braking force more than 450% greater than in rearfoot strike runners, we observed the opposite association. However, braking force has been shown to be highly variable across individuals (126). Another study comparing foot strike pattern and ground reaction force found much higher posterior loading rates in forefoot strike runners, but overall peak braking force was similar between foot strikes (42). The Pearson correlation analysis in Chapter 3 did not show a significant correlation in either direction between peak braking force and foot strike angle, though, and it was only after accounting for speed and step length that foot

strike angle became a significant contributor to the model. Therefore, the clinical usefulness of this strategy is questionable.

Despite the conflicting findings, to reduce vertical loading rates, we do suggest moving from a rearfoot strike to a more forefoot strike is an appropriate gait retraining intervention. This has the functional effect of lengthening the lever arm of the lower extremity, producing a larger arc in the vertical trajectory of the centre of mass (79). Oft-used clinical measures such as shank angle and hip flexion angle do not appear to contribute significantly to the variance of these kinetic risk factors. Furthermore, heel to centre of mass distance—often cited as a measure of overstriding (61,66)—appears to have little to contribute to a reduction in peak braking force after accounting for speed, step length, and foot strike angle. It is also negatively associated with vertical loading parameters, possibly owing to the increasing vertical orientation of the ground reaction force vector with decreasing heel to centre of mass distance.

5.3 Gait retraining to reduce kinetic and kinematic risk factors of running-related injuries

Recent studies have shown the potential substantial benefit of gait retraining (22,66). Vertical loading rates may be lowered through a gait retraining intervention using real-time biofeedback of the vertical ground reaction force or tibial acceleration (22,69,70). The most effective interventions have relied on lab-based feedback of kinetic metrics (71), but in a clinical setting, it is not always feasible to provide real-time feedback of the ground reaction force variables due to constraints on equipment, costs, and analytic methods. Many kinematic variables can be measured and modified in a clinical setting, however, using 3D motion capture or even 2D video (76,77).

Our results from Chapter 4 showed that peak braking force can be modified using real-time biofeedback of braking forces, and that average vertical loading rate and instantaneous vertical loading rate can also be significantly reduced as an added benefit. Our analysis revealed that runners reduced their peak braking force primarily by decreasing their step length and increasing their step frequency, which corresponds to our findings in Chapter 3. Also in agreement with our results from Chapter 3, heel to sacrum distance—a surrogate measure for heel to centre of mass distance—and shank angle at initial contact were no different between baseline and follow-up, suggesting that these variables are not as important as step length/rate when reducing peak braking force. Foot strike angle also did not change from baseline to follow-up, even though it was part of our model to explain peak braking force and vertical loading rates in Chapter 3. Several previous studies have also linked foot strike angle to vertical loading rate (53,62,79). However, as stated above, the Pearson correlation analysis in Chapter 3 did not show a significant correlation between peak braking force and foot strike angle, and it was only after accounting for speed and step length that foot strike angle became a significant contributor to the model. This fits with findings from Bowersock et al (119) who reported that reductions in several kinetic parameters, including braking impulse, were related to decreases in step length, but not changes in foot strike pattern. The importance of this result is that it suggests that an increase in step frequency—or decrease in step length—does not necessarily need to be accompanied by a change in foot strike angle in order to produce a significant reduction in peak braking force and vertical loading rate.

5.4 Limitations

There are some limitations to the studies contained within this thesis. These include the generalizability of some results and the absence of a control group in Chapter 4. These limitations are detailed below.

1) Our study samples consisted solely of female novice runners between the ages of 18 and 60 years old. This was a conscious decision in recognition of the differences in biomechanical risk factors between males and females (20) and the different risk profiles between novice and trained runners (4-7). While the results from Chapter 2 may not be generalizable to males or trained runners, results from Chapter 3 should not be affected, as Wille et al (62) found that sex did not directly affect the relationship between kinematic variables and kinetic outcomes and these same biomechanical relationships should still hold true among trained runners. Furthermore, as long as the principles of the training protocol in Chapter 4 are adhered to, we see no reason that males and trained runners could not follow the same gait retraining program and see the same benefits as female novice runners. However, we encourage future research of this nature in males and in trained runners.

2) The study in Chapter 2 grouped all prospective injuries together and did not differentiate between specific injuries. Given that variables such as average vertical loading rate have been most often linked to specific injuries such as tibial stress fracture (24,28,31), this may have affected the strength of our results. However, even with this approach, we found a 500-800% increased injury risk for higher peak braking force (our primary outcome) and as a result this may be generalized to all running-related injury, not just a specific injury type.

3) All biomechanical analyses were conducted on an instrumented treadmill and while kinetics have been shown to be similar between treadmill and overground running (90,91),

some differences in kinematics have been documented (decreased step length and heel to centre of mass distance (110); more flexed knee at initial contact (110); more midfoot/forefoot strike (110,111)). This may have influenced our results throughout and might limit the generalizability of these results to overground running. An important next step would be to replicate our findings for overground running.

4) The intervention study in Chapter 4 was designed to be preliminary in nature, in order to test whether individuals could be retrained to reduce their peak braking force. Due to the absence of a control group, we cannot suggest that this intervention is superior to a half-marathon training program alone. However, it is unlikely that the biomechanical changes seen would have occurred without the retraining program (122). A randomized controlled trial with a longer follow-up period is warranted to compare this type of gait retraining program to one that could be carried out in a clinical environment using kinematic cues.

5) Finally, it is unknown whether the gait modifications in Chapter 4 that were observed in the laboratory were transferred to the community. Given the increasing availability and capability of wearable devices, data should be collected in the community to determine whether transference from the lab is occurring (123,124).

5.5 Implications of the research

The above chapters detail investigations into biomechanical risk factors of running-related injury. Given the estimated 17 million runners who participate annually in recreational running events in the United States alone (3), in addition to the millions more who run for health benefits (2), this is an important area of study.

The link between peak braking force and running-related injuries has not been previously established. The significance of our results—notably a five to eight-fold increase in injury risk with higher peak braking force—is both novel and clinically meaningful. Furthermore, the lack of a clear association between average vertical loading rate and injury risk adds to the debate over the importance of this variable in the development of running-related injury.

While overstriding has been cited as a potential risk factor of running-related injury, there is no consensus definition of overstriding and there has been little evidence to support the importance of overstriding to running-related injury risk (66). Results from Chapters 3 and 4 contribute to an outcome-based definition of overstriding based on higher peak braking force. Specifically, step length more than heel to centre of mass distance appears to have a greater effect on peak braking force after accounting for speed. Furthermore, oft-used clinical measures such as shank angle and hip flexion angle do not appear to influence vertical or anterior-posterior loading.

Our final study also demonstrated that peak braking force—and as an added benefit, vertical loading rate—can be reduced via real-time biofeedback of performance. Based on verbal feedback from participants and confirmed by kinematic outcomes collected at baseline and follow-up, these reductions may be achieved by modestly reducing step length and increasing step frequency. Importantly, a reduction in speed, heel to centre of mass distance, shank angle, or a change in foot strike pattern are not necessary to achieve a clinically significant reduction in anterior-posterior and vertical loading parameters.

5.5.1 Implications for the clinical management of running-related injuries

There is significant clinical importance from the above findings. First, the addition of peak braking force to the biomechanical risk factor literature guides the clinician to consider this variable in the lab (if access is available) or via surrogate kinematic measures such as step length. This is the first prospective study to demonstrate this link. The vulnerability of bones—and possibly other tissues—to withstand shear (horizontal) forces compared to compressive (vertical) forces, may be one mechanism by which peak braking force increases injury risk (40,41). Furthermore, novice runners may be at increased risk of injury compared to experienced runners due to a reduced ability to withstand higher loading rates, and this vulnerability may be more apparent in the braking component than the vertical component due to the increase in these forces at the start of a running program.

The results from the previous chapters suggest that gait retraining to reduce peak braking force—and therefore running-related injury risk—is both appropriate and effective. Even before beginning a gait retraining program, clinicians can offer some basic advice based on our findings. For instance, the substantial effect of speed on peak braking force suggests that limiting speed early on in a training program is advisable until some adaptation to these forces has occurred. Furthermore, maintaining a shorter step length would also be prudent for the novice runner based upon our findings from Chapters 3 and 4.

For runners wanting to decrease injury risk, the findings from our series of studies point to several potential interventions. For runners with high peak braking force, shortening step length has the effect of reorienting the ground reaction force vector less posteriorly, thus decreasing the braking force. Clinically, this may easily be retrained without the use of a specialized lab, simply by cueing the runner to increase their step frequency by approximately

7% to the beat of a metronome. Such metronomes are readily available as smart phone applications. A shortened step length also has the added benefit of decreasing vertical loading rates (average vertical loading rate and instantaneous vertical loading rate), which have been implicated as running-related injury risk factors in several other studies (18,20,24,31).

While changing foot strike pattern—specifically, from a rearfoot strike to a forefoot strike—is often recommended (18,53,66), our findings suggest that this may not be necessary after addressing step length. In support of our findings, Bowersock et al (119) reported that reductions in several kinetic parameters, including braking impulse, were related to decreases in step length, but not changes in foot strike pattern. The importance of this result is that it suggests that an increase in step frequency—or decrease in step length—does not necessarily need to be accompanied by a change in foot strike angle in order to produce a significant reduction in peak braking force and vertical loading rate.

Changing foot strike pattern has the potential to stress other structures, such as the foot and Achilles tendon, increasing risk of injury in those tissues. In a systematic review of the effect of running gait modifications, we found that distal kinematics were affected to a greater degree than proximal kinematics when foot strike was manipulated, likely due to the increased internal focus on the foot strike angle by the individual (71). Therefore, changing a runner's gait via a global mechanism with an external focus, such as step frequency, without altering foot strike, may be safer.

Importantly, oft-used clinical measures such as shank angle and hip flexion angle at initial contact do not appear to influence peak braking force significantly based on our results from Chapters 3 and 4. Therefore, we do not recommend targeting these measures clinically. Furthermore, heel to centre of mass distance—often cited as a measure of overstriding (61,66)—

appears to have little to contribute to a reduction in peak braking force after accounting for speed and step length. It is also negatively associated with vertical loading parameters owing to the increasing vertical orientation of the ground reaction force vector with decreasing heel to centre of mass distance.

Interestingly, when runners in our final study were asked what their strategy was to reduce their braking forces, the cue to "run softer" was reported by 42% of participants. Interestingly, this was one of several cues given by therapists to runners with patellofemoral pain in the gait retraining group in the randomized controlled trial by Esculier et al (75). While braking forces were not reported in that study, average vertical loading rate decreased by 26% from baseline to follow-up in the gait retraining group. This cue was also used in a study comparing the effectiveness of a gait retraining program using therapist feedback versus real-time feedback of tibial acceleration (78). That study reported equal effectiveness of both modes of retraining, resulting in similar reductions in tibial acceleration. Given the results from these studies, along with the information from Chapter 4, this cue is likely worthwhile in a clinical setting.

5.5.2 Implications for future research

Future research should focus on reproduction of the above studies in different populations (e.g. males, trained runners) and in overground running to be able to further generalize these results. In addition, after proving the feasibility of a gait retraining program to reduce peak braking forces via real-time biofeedback, a randomized controlled trial is recommended to evaluate this program against a more clinically-feasible intervention (e.g. step frequency modification). Such a trial could also incorporate a larger sample to assess the

influence on injury rates and a longer follow-up period to assess retention of the modified gait pattern and kinetic outcomes.

With the improvement and availability of wearable technology, taking the findings from this series of studies out of the lab and into the community would allow further generalizability of the results and more practical application. For instance, inertial measurement units (IMUs) have been shown to reliably measure kinetics and kinematics over a marathon event (127). Various biomechanical changes were noted between the beginning and end of the race that are most likely explained by fatigue. If some of the above noted detrimental biomechanics are found to occur with fatigue at the end of long runs, this may contribute to our understanding of the development of running-related injury. Further, if these devices can deliver real-time biofeedback of these parameters, there may be the opportunity to modify gait to protect from injury (123).

Importantly, average vertical loading rate has been highly correlated with tibial shock (r^2=0.95), a measure which can be easily quantified by an accelerometer mounted distally on the tibia (124). Though it has not been examined directly, it is likely that braking force could also be estimated by a distally-mounted accelerometer. Reproducing the studies contained in Chapter 2 and 3 using wearable devices in the community would not only make the results more generalizable, but also give greater depth of knowledge about how runner's mechanics change in different environments, fatigue states, and over the course of a training program. This would further inform a gait retraining program that could potentially use real-time biofeedback of braking forces in the community via wearable technology.

5.6 Conclusion

This thesis provides new insight into the risk factors of running-related injuries and the potential treatment strategies to reduce these risk factors. The identification of peak braking force as a significant risk factor of running-related injury, in addition to the kinematic variables correlated with this parameter and vertical loading parameters has direct clinical application. Furthermore, the gait retraining program evaluated in this thesis demonstrates that runners have the ability to reduce their peak braking force and it provides the framework for a larger, randomized controlled trial of the role of gait retraining to reduce running-related injury risk.

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Appendices

Appendix A 15-week half-marathon training program

	Run 1– Workout	**Run 2 – Easy Run / Lab Visit**	**Run 3 – Workout**	**Run 4 – Long Run**
Week 1 -> 5 Hill/Lactate Capacity Phase	**Every workout is to be preceded by 10 mins of easy running and mobility routine.**		**Every workout is to be preceded by 10 mins of easy running and mobility routine.**	
Week 1	5 x 4:00 * Pace Target: Lactate Threshold * Recovery: 1:00 walk after each fast run.	30 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	Lactate Capacity Hills (moderate grade): 4 x 45 seconds + 4 x 30 seconds + 4 x 15 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain your pace within each set and increase your pace as the hills get shorter in duration. * Recovery: 1.5 minutes jog down after each hill.	60 minutes easy
Week 2	Lactate Capacity Hills (moderate grade): 8 x 45 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain or increase your pace slightly on each hill. * Recovery: 1.5 minutes jog down after each hill.	35 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	:30 - :45 - 1:00 - 1:15 - 1:30 - 1:45 - 2:00 - 2:00 - 1:45 - 1:30 - 1:15 - 1:00 - :45 - :30 * Pace Target: 3 km goal pace average. The :30 runs should be up to 20 seconds/km faster than 3 km goal pace and the 2:00 runs should be up to 20 seconds slower than 3 km goal pace. * Recovery: 1:15 walk after each hard run.	70 minutes easy
Week 3	8 x 3:00 * Pace Target: 10 km Goal Pace * Recovery: 1:00 walk after each hard run.	40 minutes easy	Lactate Capacity Hills (moderate grade): 3 x 60 seconds + 3 x 45 seconds + 3 x 30 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain your pace within each set and increase your pace as the hills get shorter in duration. * Recovery: 2 minutes jog down after each hill.	70 minutes easy + 10 minutes at half marathon goal pace

Week 4	Lactate Capacity Hills (moderate grade): 10 x 60 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain or increase your pace slightly on each hill. * Recovery: 2 minutes jog down after each hill.	40 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	3 sets of (2:00 - 1:45 - 1:30 - 1:15 - 1:00) * Pace Target: 5 km goal pace average. Start out 10 seconds/km slower than 5 km goal pace and increase your pace by 5 to 10 seconds/km as the runs get shorter in duration. * Recovery: 1:00 walk after each hard run.	10 minutes easy + 60 minutes alternating 5 minutes at half marathon goal pace with 5 minutes 30 seconds/km slower than half marathon goal pace
Week 5 **EASY WEEK**	2 x 8:00 * Pace Target: Lactate Threshold * Recovery: 2:00 walk between each fast run.	30 minutes easy	30 minute easy + 10 x 20 seconds uphill (moderate grade) strides with 40 seconds jog down recovery	60 minutes easy

Week 6 -> 10 VO2 Max Phase	**Run 1– Workout**	**Run 2 – Easy Run / Lab Visit**	**Run 3 – Workout**	**Run 4 – Long Run**
Week 6	Lactate Capacity Hills (moderate grade): 3 x 75 seconds + 3 x 60 seconds + 3 x 45 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain your pace within each set and increase your pace as the hills get shorter in duration. * Recovery: 2 minutes jog down after each hill.	45 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	:30 - 1:00 - 1:30 - 2:00 - 2:30 - 2:30 - 2:00 - 1:30 - 1:00 - :30 * Pace Target: 3 km goal pace average. The :30 runs should be up to 30 seconds/km faster than 3 km goal pace and the 2:30 runs should be up to 20 seconds slower than 3 km goal pace. * Recovery: 1:30 walk after each hard run.	75 minutes easy + 15 minutes at half marathon goal pace
Week 7	14 x 2:00 * Pace Target: 5 km Goal Pace * Recovery: 1:00 walk after each hard run.	50 minutes easy	7:00 - 6:00 - 5:00 - 4:00 - 3:00 - 2:00 - 1:00 * Pace Target: 10 km goal pace average. Start out 20 seconds/km slower than 10 km goal pace and increase your pace by 5 to 10 seconds/km as the runs get shorter in duration. * Recovery: 1:00 walk after each hard run.	100 minutes alternating 20 minutes easy with 5 minutes at half marathon goal pace
Week 8	Lactate Capacity Hills (moderate grade): 8 x 75 seconds	50 minutes easy / Gait Retraining Session @ Fortius	6 x 3:00 * Pace Target: 3 km goal pace. * Recovery: 3:00 walk after each hard run.	10 minutes easy + 75 minutes alternating 10 minutes at half marathon goal pace with 5 minutes at 30 seconds/km slower than half marathon goal pace

	* Effort: As hard as you can run while maintaining form and relaxation. Try to maintain or increase your pace slightly on each hill. * Recovery: 2.5 minutes jog down after each hill.	Biomechanics Lab	* This is a test session and will be repeated in week 14.	
Week 9	5:00 - 4:30 - 4:00 – 3:30 – 3:00 - 2:30 - 2:00 - 1:30 - 1:00 - :30 * Pace Target: 5 km goal pace average. Start out 20 seconds/km slower than 5 km goal pace and increase your pace by 5 to 10 seconds/km as the runs get shorter in duration. * Recovery: 1:30 walk after each hard run.	55 minutes easy	20 minutes at Lactate Threshold * This is a test session and will be repeated in week 14.	85 minutes easy + 25 minutes at half marathon goal pace
Week 10 **EASY WEEK**	2 x 10:00 * Pace Target: Lactate Threshold * Recovery: 2:00 walk between each fast run.	30 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	10 x :30 * Pace Target: 3 km goal pace. * Recovery: :30 walk after each hard run.	65 minutes easy
Week 11 -> 15 Lactate Threshold Phase	**Run 1– Workout**	**Run 2 – Easy Run / Lab Visit**	**Run 3 – Workout**	**Run 4 – Long Run**
Week 11	Lactate Capacity Hills (moderate grade): 3 x 90 seconds + 3 x 75 seconds + 3 x 60 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain your pace within each set and increase your pace as the hills get shorter in duration. * Recovery: 2.5 minutes jog down after each hill.	55 minutes easy	30 minute Pace-Change Run (alternating 3 minutes hard with 2 minutes float) * Run as fast as you can while keeping the difference between the hard sections and floats to no more than 25 seconds/km. Start with :10/km faster than Lactate Threshold on the hard sections and :15/km slower than Lactate Threshold on the floats and adjust from there depending on how you're feeling.	10 minutes easy + 80 minutes alternating 15 minutes at half marathon goal pace with 5 minutes at 30 seconds/km slower than half marathon goal pace

Week 12	6 x 6:00 * Pace Target: 10 km Goal Pace * Recovery: 2:00 walk after each hard run.	60 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	2:00 - 3:00 - 4:00 - 5:00 - 5:00 - 4:00 - 3:00 - 2:00 * Pace Target: 5 km goal pace average. The 2:00 runs should be up to 20 seconds/km faster than 3 km goal pace and the 5:00 runs should be around 10 seconds slower than 5 km goal pace. * Pace Target: 5 km goal pace average. Start out 20 seconds/km slower than 5 km goal pace and increase your pace by 10 to 20 seconds/km as the runs get shorter in duration. * Recovery: 2:00 walk after each hard run.	2 hours alternating 30 minutes easy with 10 minutes at half marathon goal pace
Week 13	Lactate Capacity Hills (moderate grade): 8 x 90 seconds * Effort: As hard as you can run while maintaining form and relaxation. Try to maintain or increase your pace slightly on each hill. * Recovery: 3 minutes jog down after each hill.	60 minutes easy	30 minute Progression Run: 6:00 @ :20/km slower than Lactate Threshold -> 6:00 @ :10/km slower than Lactate Threshold -> 6:00 @ Lactate Threshold -> 6:00 @ :10/km faster than Lactate Threshold -> 6:00 @ :20/km faster than Lactate Threshold	10 minutes easy + 80 minutes at half marathon goal pace
Week 14	20 minutes at Lactate Threshold	40 minutes easy / Gait Retraining Session @ Fortius Biomechanics Lab	6 x 3:00 * Pace Target: 3 km goal pace. * Recovery: 3:00 walk after each hard run.	30 minutes easy + 45 minutes alternating 5 minutes at half marathon goal pace with 10 minutes easy
Week 15 **TAPER WEEK** **Follow-up Lab Test**	32 minute Progression Run: 8 minute easy + 8 minutes at :10 to :20/km slower than half marathon goal pace + 8 minutes at half marathon goal pace + 8 minutes at Lactate Threshold	20 minutes easy	10 minutes + 6 x 30 seconds * Pace Targets: 10 minute run: Lactate Threshold 30 seconds runs: 3 km goal pace * Recovery: 2 minutes after the 10 minute run and 30 seconds walk between the 30 second runs.	Half Marathon

Appendix B Weekly Online Questionnaire

UBC Run Study

Please answer all questions below. All questions pertain to the previous week (Monday to Sunday).

* Required

1. **Please enter your participant ID you were assigned at the start of the study (UBCRUN___):** *

   Enter the number that follows "UBCRUN"

2. **How much did you run in the last week (Monday to Sunday)?** *

   Example: 4:03:32 (4 hours, 3 minutes, 32 seconds)

3. **Did you complete all workouts as prescribed in the last week (Monday to Sunday)?** *

   Mark only one oval.

   - Yes
   - No

UBC Run Study

Rating of Perceived Exertion Scale

6	No exertion at all	20% effort
7	Extremely Light	35% effort
8		
9	Very Light	50% effort
10		55% effort
11	Light	60% effort
12		65% effort
13	Somewhat Hard	70% effort
14		75% effort
15	Hard (Heavy)	80% effort
16		85% effort
17	Very Hard	90% effort
18		95% effort
19	Extremely Hard	100% effort
20	Maximal Exertion	Exhaustion

4. **Please rate your effort for the following runs in the last week based on the scale above (Monday to Sunday)** *

Individual Run 1

Mark only one oval.

- Did not complete workout
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20

5. **Please rate your effort for the following runs in the last week based on the scale above (Monday to Sunday)** *

Thursday - Group Workout

Mark only one oval.

- Did not complete workout
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20

6. **Please rate your effort for the following runs in the last week based on the scale above (Monday to Sunday)** *
Individual Run 2
Mark only one oval.

- Did not complete workout
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20

7. **Please rate your effort for the following runs in the last week based on the scale above (Monday to Sunday)** *
Sunday - Group Long Run
Mark only one oval.

- Did not complete workout
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20

UBC Run Study

8. **Did you do any other physical activity or extra running this week?** *
Mark only one oval.

- Yes
- No *Skip to question 10.*

UBC Run Study

9. **Please describe what extra physical activity or running you did this week**
   Be as specific as possible (type, frequency, duration, intensity)

UBC Run Study

10. **Did you have any pain in your body in the last week (Monday to Sunday)?** *
    Mark only one oval.

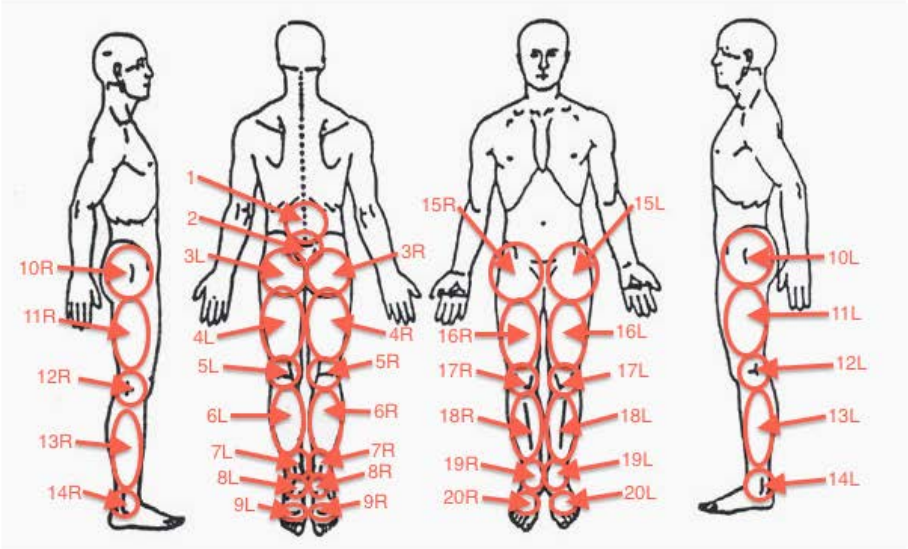
    - Yes
    - No *Skip to question 53.*

UBC Run Study

11. **How many training days did you miss this week (Monday to Sunday) due to pain?** *
    Please only indicate days missed due to pain, not because of other reasons.
    Mark only one oval.

    - 0
    - 1
    - 2
    - 3
    - 4

Pain regions


1
2
3L
3R
4L
4R
5L
5R
6L
6R
7L
7R
8L
8R
9L
9R
10R
11R
12R
13R
14R
15R
15L
16R
16L
17R
17L
18R
18L
19R
19L
20R
20L
10L
11L
12L
13L
14L

12. **Please check any areas where you have experienced any pain in the last week (Monday to Sunday)** *
Check as many areas as apply.
Check all that apply.

- [ ] Area 1 (Low Back)
- [ ] Area 2 (Tailbone)
- [ ] Area 3 (Buttock)
- [ ] Area 4 (Back of thigh)
- [ ] Area 5 (Back of knee)
- [ ] Area 6 (Calf)
- [ ] Area 7 (Achilles)
- [ ] Area 8 (Bottom of heel)
- [ ] Area 9 (Bottom front of foot)
- [ ] Area 10 (Outside of hip)
- [ ] Area 11 (Outside of thigh)
- [ ] Area 12 (Outside of knee)
- [ ] Area 13 (Outside of lower leg)
- [ ] Area 14 (Outside of ankle)
- [ ] Area 15 (Front of hip)
- [ ] Area 16 (Front of thigh)
- [ ] Area 17 (Front of knee)
- [ ] Area 18 (Shin)
- [ ] Area 19 (Inside of ankle)
- [ ] Area 20 (Top of foot)
- [ ] Other: _____

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

13. **Area 1 (Low Back)**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

14. **Area 2 (Tailbone)**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

15. **Area 3 (Buttock) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

16. **Area 3 (Buttock) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

17. **Area 4 (Back of thigh) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

18. **Area 4 (Back of thigh) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

19. **Area 5 (Back of knee) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

20. **Area 5 (Back of knee) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

21. **Area 6 (Calf) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

22. **Area 6 (Calf) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

23. **Area 7 (Achilles) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

24. **Area 7 (Achilles) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

25. **Area 8 (Bottom of heel) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

26. **Area 8 (Bottom of heel) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

27. **Area 9 (Bottom front of foot) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

28. **Area 9 (Bottom front of foot) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

29. **Area 10 (Outside of hip) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

30. **Area 10 (Outside of hip) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

31. **Area 11 (Outside of thigh) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

32. **Area 11 (Outside of thigh) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

33. **Area 12 (Outside of knee) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

34. **Area 12 (Outside of knee) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

35. **Area 13 (Outside of lower leg) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

36. **Area 13 (Outside of lower leg) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

37. **Area 14 (Outside of ankle) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

38. **Area 14 (Outside of ankle) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

39. **Area 15 (Front of hip) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

40. **Area 15 (Front of hip) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

41. **Area 16 (Front of thigh) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

42. **Area 16 (Front of thigh) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

43. **Area 17 (Front of knee) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

44. **Area 17 (Front of knee) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

45. **Area 18 (Shin) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

46. **Area 18 (Shin) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

47. **Area 19 (Inside of ankle) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

48. **Area 19 (Inside of ankle) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

Only answer this question if you indicated that you had pain in this region on the pain diagram above.

49. **Area 20 (Top of foot) - Left**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

50. **Area 20 (Top of foot) - Right**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

UBC Run Study

51. **Other area (please indicate)**
Please describe the area that you experienced pain if it does not fit into an area above

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52. **Other area**
Indicate the worst level of pain you have experienced in this body area over the last week (Monday to Sunday) while taking part in, or immediately after, a run session
Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
No pain	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Worst pain imaginable

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53. **Do you have any general comments regarding your training over the last week (Monday to Sunday)?**

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