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EFFECTS OF A VISUAL-FEEDBACK GAIT RETRAINING TO PROMOTE MIDFOOT LANDING PATTERN IN RUNNERS

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Effects of a Visual-feedback Gait Retraining to Promote Midfoot Landing Pattern in Runners

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the degree of Master of Philosophy

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Chan Yau Shan Zoe

ABSTRACT

Distance running has become a popular way to exercise across the world. Unfortunately, it also came with a high risk of injuries. Biomechanical factors such as high impact loading and striking with the rearfoot have demonstrated associations with running-related injuries, and gait modification has been proposed to correct improper running form among the runners at-risk. This thesis examined the effectiveness of two gait retraining programs, focusing on the clinical effect for injury prevention and biomechanical effect for impact loading reduction.

In the first study (Chapter 3), two groups of novice runners were assessed on running kinetics and injury. The training group underwent a lab-based gait retraining for two weeks, softening their footfalls with the help of visual feedback. Upon completion of the training, impact loading was lowered in the trained runners. More importantly, within one year of training, the injury occurrence of the training group was found to be 62% lower than the controls. This study has underlined the clinical significance of reducing impact loading through gait retraining.

The study outlined in Chapter 4 and 5 provided a comprehensive evaluation of a gait retraining program that promoted midfoot landing. Runners who habitually ran with a rearfoot strike underwent gait retraining. Real-time footstrike information was provided while they were modifying their gait. The training was found effective in reducing runners’ footstrike angle, but not necessarily lead to a complete transition of footstrike pattern. Such reduction in footstrike angle could be maintained for a month. Surprisingly, the changes in impact loading were inconsistent among the trained runners, indicating that this training could be beneficial to certain runners, but not all.

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2. Chan, Z.Y.S., Zhang, J.H., Au, I.P.H., An, W.W., Shum, G.L.K., Ng, G.Y.F., Cheung, R.T.H., 2017. Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial. The American Journal of Sports Medicine 036354651773627. https://doi.org/10.1177/0363546517736277

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2. Chan, Z.Y.S., Zhang, J.H., Ferber, R., Shum, G.L.K., Cheung, R.T.H Effect of midfoot strike gait retraining on impact loading and joint stiffness (*Medicine & Science in Sports & Exercise*, under review)

Conference presentations:

1. Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, Pun, G.T.K., An, W.W., Cheung, R.T.H., 2017. Gait retraining reduces impact loading and injury risk in novice runners. The XXVI Congress of the International Society of Biomechanics (ISB 2017), 23 - 27 July 2017, Brisbane, Australia.
2. Cheung, R.T.H., Lau, F.O.Y., Ching, E.C.K., Chan, Z.Y.S., Zhang, J.H., Au, I.P.H., 2017. Maximalist shoes do not reduce impact loading during level and downhill running. Medicine & Science in Sports & Exercise. 49(5S):132. American College of Sports Medicine 64th Annual Meeting, 30 May - 3 June 2017, Denver, Colorado USA.
3. Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, An, W.W., Cheung, R.T.H., 2017. Effects of deceptive footwear condition on subjective comfort and joint kinematics in runners. The 5th HKASMSS Student Conference, 26 November 2016, Hong Kong.
4. Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, An, W.W., Cheung, R.T.H., 2017. Effects of a visual-feedback gait retraining on landing pattern transition in rear-foot strike runners. The 5th HKASMSS Student Conference, 26 November 2016, Hong Kong.

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2. Chan Z.Y.S., Lau F.O.Y., Ching E.C.K., Zhang J.H., Au I.P.H., Cheung R.T.H. (2018) Enhanced Shoe Cushioning: Are they More Comfortable and Better in Impact Attenuation during Level and Downhill Running? 11th Pan Pacific Conference on Rehabilitation, 17-18 November, 2018, Hong Kong.

3. Chan Z.Y.S., Zhang J.H., Au I.P.H., An W.W., Cheung R.T.H. (2018) Biased Perception of Footwear Comfort in Runners: a Deceptive Cross-over study. 11th Pan Pacific Conference on Rehabilitation, 17-18 November, 2018, Hong Kong.

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LIST OF ABBREVIATIONS

RRI	Running-related injury
BW	Bodyweight
GRF	Ground reaction force
VIP	Vertical impact peak
VALR	Vertical average loading rate
VILR	Vertical instantaneous loading rate
PPA	Peak positive acceleration
RFS	Rearfoot strike
MFS	Midfoot strike
FFS	Forefoot strike
MAX	Maximalist
CON	Conventional footwear
NHS	Non-heelstrike
FSA	Footstrike angle
RCT	Randomized controlled trial
SD	Standard deviation
MIN	Minimalist
HS	Heelstrike

CHAPTER 1

INTRODUCTION

1.1 Injuries in runners

Running is becoming more popular since the late 1960s (Novacheck, 1998). The strong evidence of health benefits, including improved aerobic fitness and cardiovascular function, has motived people across the world to take their first step and continued running (Oja et al., 2015; Williams, 2009). Running has become one of the top five popular physical exercise practiced by individuals of all age (Hulteen et al., 2017). Unfortunately, an increase in the prevalence of running-related injuries (RRIs) is concurrent to the increase in the running population. Specifically, 37-79% of runners would sustain an RRI in a given year (Bovens et al., 1989; Lun et al., 2004; van Gent et al., 2007) and with an injury risk of up to 12 RRIs per 1,000 hours of running (Bovens et al., 1989).

An RRI can affect not merely the pleasure and performance of an individual, but the detrimental effect on health and daily life and the economic burden on the healthcare system are also significant (Hespanhol Junior et al., 2016). On that account, it is important to identify possible risk factors and outline strategies to prevent RRIs. With that said, a definite cause of injury has yet been identified, owning to the multifactorial origin of RRIs (van der Worp et al., 2016). Series of studies have underlined the etiology related to RRIs, which could be categorized into intrinsic and extrinsic factors. Examples of intrinsic risk factors include anthropometric variations (Wen et al., 1997), history of previous injury (Van Middelkoop et al., 2008; van Poppel et al., 2018) and running biomechanics (Hreljac, 2005), while extrinsic risk factors include training errors (Nielsen et al., 2012), running surface (Wen et al., 1997) and footwear (Goss and Gross, 2012; Ryan et al., 2014). Specific combinations of various risk factors could induce a particular type of RRI.

Large-scale studies of RRIs indicate the knee sustains the highest rate of injury, with 22.4 to 42.1% among all RRIs (Goss and Gross, 2012; Taunton et al., 2002), followed by the foot and ankle (16.9% to 31.2%) and the lower leg (12.8% to 16.7%). The most common overuse injuries were patellofemoral pain, iliotibial band syndrome, plantar fasciitis, Achilles tendinitis and shin splints (Goss et al., 2015; Taunton et al., 2002; van Gent et al., 2007). While runners sustain a few acute injuries like ankle sprain, overuse injuries are a lot more common (Tschopp and Brunner, 2017). Knobloch *et al.* reported overuse injury being seven times more likely than an acute injury (Knobloch et al., 2008). This phenomenon might be explained by the nature of running. Running involves repeated collisions between the body with the ground, and with each footstrike, runners were exposed to a ground reaction force of approximately 2.5 times of their bodyweight (BW) (Cavanagh and Lafortune, 1980). An overuse injury could result from the combined stress to the musculoskeletal structures in the body over an extended period of time, and could be avoided by reducing the stress to below the injury threshold (Hreljac, 2005; Stanish, 1984). Methods have been suggested to determine the injury threshold and in turn mitigate the risk of RRIs from different perspectives; one of which is through biomechanical analyses.

1.2 Biomechanical risk factors of running-related injuries

Research which focused on various biomechanical gait variables has caught on to the increasing running population. A substantial amount of research has put focus on kinetics, kinematics and the relationship between them. Particular variables including impact loading, footstrike pattern and joint stiffness have been studied and proposed as possible risk factors of injury.

1.2.1 Impact loading

Almost all the biological tissues in the human body are viscoelastic owning to its anatomical and biomechanical structure (Sasaki, 2012). The human bone (Kemper et al., 2008), ligaments (Criscenti et al., 2015; Dommelen et al., 2005) and muscle-tendon units (Taylor et al., 1990) all display a viscoelastic behaviour, and its failure is rate-dependent. The damage is therefore subjected to how rapidly the force is applied, instead of the absolute magnitude. This viscoelastic property of the tissue explained the association of RRIs with the rate of impact loading rather than the amplitude of the impact force (Milner et al., 2006).

Upon foot-ground contact, an immediate increase in force is experienced by the runner. This sudden and large impact force has been associated with various types of RRIs, and reflected as the impact loading. Specific RRIs found to be associated include patellofemoral pain (Cheung and Davis, 2011), plantar fasciitis (Pohl et al., 2009) and tibial stress fracture (Milner et al., 2006; Pohl et al., 2008).

The magnitude of impact loading could be derived from the vertical ground reaction force (GRF) curve, and was often measured as loading rates

(Crowell et al., 2010). Referring to a previous study (Crowell et al., 2010), a vertical impact peak (VIP) was identified from the vertical GRF-time curve as the local maximum within the first 50 ms of foot-ground contact. The linear portion between the 20% and 80% point of the VIP was defined as the region of interest (Figure 1.1). The vertical average (VALR) and instantaneous (VILR) loading rate were defined as the average and maximum slope within that region of interest. Increased loading rates has been reported to be significantly associated with RRIs in both retrospective and prospective studies (Davis et al., 2016; Hreljac et al., 2000). As for instance, Davis *et al.* performed a prospective study on 249 female runners, runners who demand medical attention for their running injury within a follow-up period of two years has VALR of 78.22±11.10 BW/s, as compared to the uninjured counterparts with VALR of 60.73±12.77 BW/s (Davis et al., 2016).

Apart from loading rates, the peak positive acceleration (PPA) of the tibia was also found to be a surrogate measurement of impact loading (Lafortune and Lake, 1995). PPA was measured by accelerometers placed on the surface of the lower leg, Zhang *et al.* measured the PPA at both the lateral melleoi and the distal tibia of ten runners (Zhang et al., 2016a). Moderate to excellent intra-subject correlations were found between PPA and VALR (r=0.480-0.950) or VILR (r=0.528-0.948). PPA measured at the lateral malleoli has a stronger correlation with VALR or VILR compared with the distal tibia. Being a good representation of impact loading experienced by a runner, high PPA has also been found to be associated with tibial stress fractures (Milner et al., 2006).

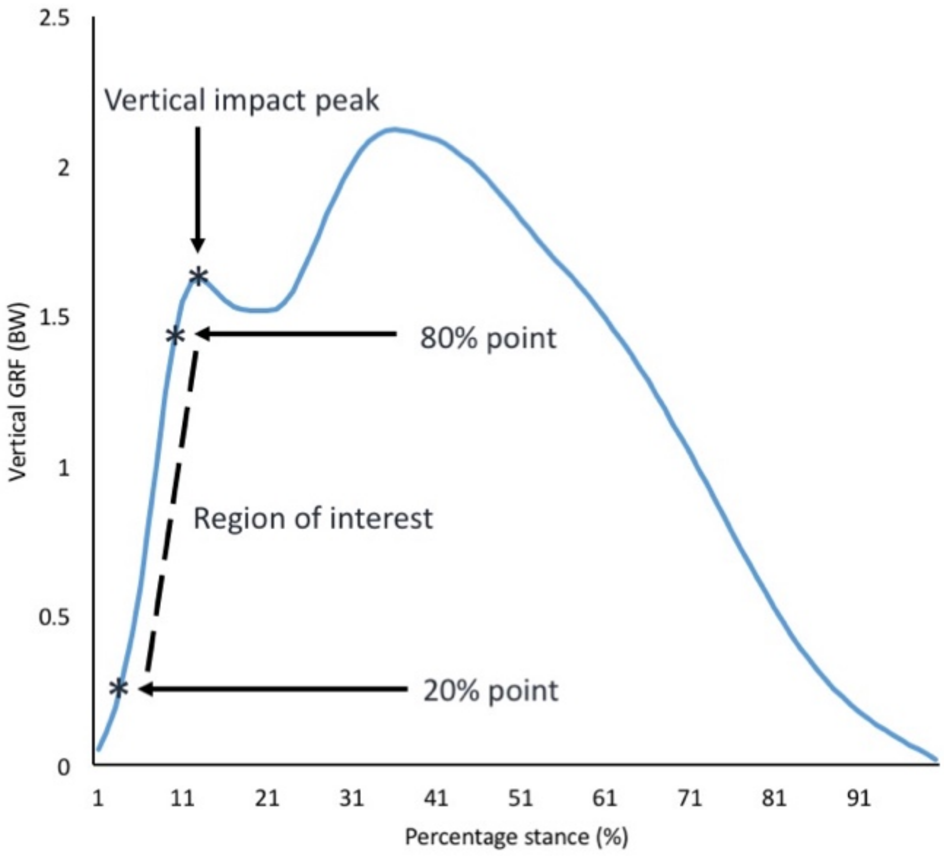

Figure 1.1 Vertical ground reaction force curve illustrating the vertical impact peak, 20% point, 80% point and the region of interest for loading rate calculation

GRF, Ground reaction force; BW, Bodyweight

1.2.2 Footstrike pattern

Footstrike pattern has also been reported as a contributing factor of RRIs (Goss et al., 2015). The footstrike pattern could be classified into rearfoot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS) based on the centre of pressure during initial foot-ground contact (Cavanagh and Lafortune, 1980) (Figure 1.2). More specifically, a RFS runner strikes with an inclined foot, with the lateral aspect of the heel touching the ground before the metatarsus. A MFS runner makes foot-ground contact with a flat foot, the metatarsal heads and heel touches the ground simultaneously. As for a FFS runner, initial contact was made using the metatarsal heads, the heel does not make contact with the ground throughout the stance phase.

A large-scale study examined the injury incidence rates among the three types of footstrike pattern, with 52.4, 34.7 and 22.8% of injury incidence among experienced RFS, MFS and FFS runners respectively (Goss and Gross, 2012). A conventional explanation for variance in injury risk among runners with different types of footstrike was linked to the impact loading. The association between loading rates and footstrike pattern has been studied for nearly 30 years. The characteristic vertical GRF curve of a RFS exhibits dual peaks; the initial peak, which is known as the VIP is coupled with a high VALR and VILR. The absence of the VIP in habitual FFS runners has been suggested as the reason behind the lower impact loading found in FFS runners (Lieberman et al., 2010) (Figure 1.3). In a more recent study, two groups of runners in their preferred footstrike pattern were studied, the VALR was almost 2-fold in RFS runners compared to FFS runners (Kulmala et al., 2013).

Apart from the general risk of RRI, the difference in injury site and type of RRIs developed between FFS and RFS runners were also noticeable. It is likely explained by the difference in running mechanics between footstrike patterns. Several studies have shown that FFS runner were exposed to a higher injury risk in the ankle and foot owning to the higher loading found in the ankle plantarflexors and the Achilles tendon (Kulmala et al., 2013; Rooney and Derrick, 2013; Williams et al., 2000). While a retrospective study quantifying the history of injuries among distance runners in a cross-country team, a significantly higher rates of repetitive stress injury was found in habitual RFS runners as compared to FFS runners (Daoud et al., 2012). Recently, Boyer and Derrick examined the iliotibial band strain of runners with different footstrike pattern, both RFS and MFS/FFS runners showed some factors that are more likely to increase the risk of iliotibial band syndrome (Boyer and Derrick, 2015).

Owning to the difference in types of RRIs between runners with different footstrike patterns and the lack of the prospective injury studies that focus on MFS runners, it is still questionable whether one footstrike pattern is more protective against RRI than the other.

Figure 1.2 Position of the foot relative to the ground for rearfoot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS)

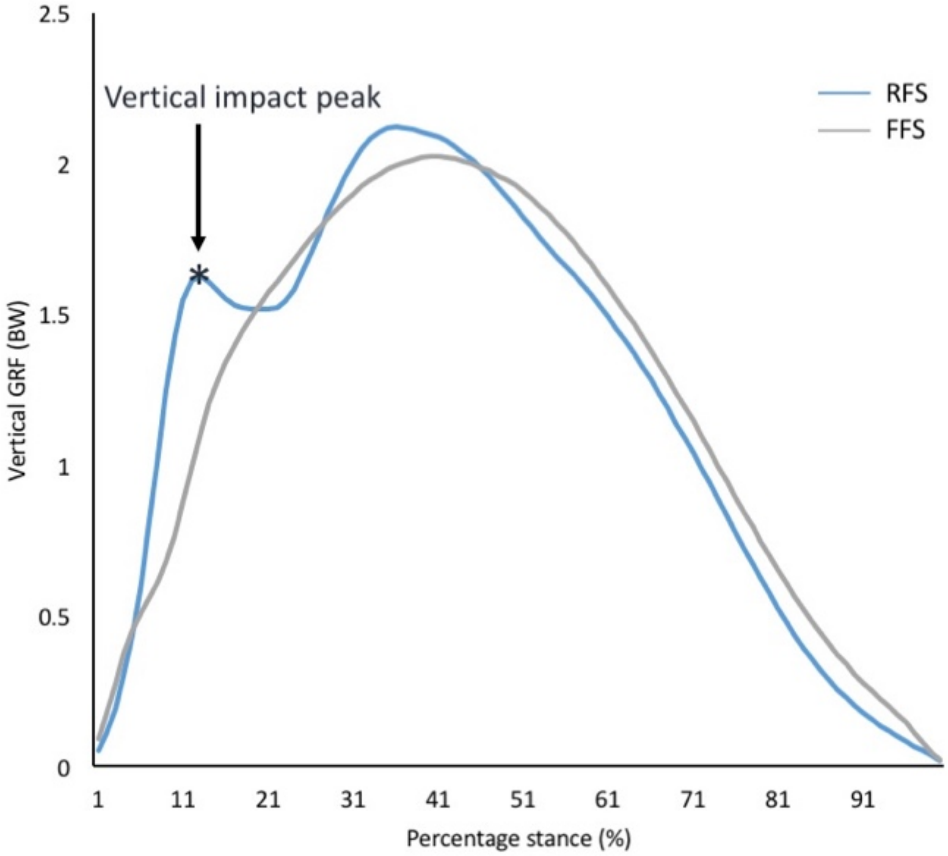

Figure 1.3 Typical vertical ground reaction force curve between rearfoot strike and forefoot strike

GRF, Ground reaction force; BW, Bodyweight; RFS, Rearfoot strike; FFS, Forefoot strike

1.2.3 Lower-limb joint stiffness

Vertical stiffness, which could be derived from the GRF, was suggested to be associated with both running performance and injury (Brazier et al., 2014; Butler et al., 2003; McMahon and Cheng, 1990). However, vertical stiffness reflects the stiffness of the entire body, and could not distinguish specific contribution by individual joints. Hamill *et al.* suggested that stiffness measured at individual joints on the lower extremity i.e. ankle and knee joint stiffness may be a more relevant indicator of lower-limb injuries (Hamill et al., 2009). The ankle and knee joint stiffness both contributes to the overall vertical stiffness within the energy absorption phase during running (Kuitunen et al., 2002) and is calculated from the moment-angle relationship of the joint. The slope in the moment-angle profile between the point of initial contact and maximum ankle dorsiflexion or knee flexion was calculated as the ankle and knee joint stiffness respectively (Hamill et al., 2014, 2009).

A runner requires certain level of stiffness in each joint for maintaining one's posture and optimal performance (Stefanyshyn and Nigg, 1998). Yet, excessively high joint stiffness would reduce the shock attenuation, it has been supported by previous studies that a stiffener joint induced harder landings (Baltich et al., 2015; Mauroy et al., 2014).

For instance, a series of studies conducted by Williams *et al.* investigated the lower extremity mechanics and injury pattern among runners with high and low arch (Williams et al., 2004, 2001). High-arched runners demonstrated greater leg and knee stiffness and sustained a significantly higher incidence of bony injuries when compared to runners with low foot arch. Although a direct relationship could not be drawn from the results of the studies, the author observed a trend of increased impact loading with the greater leg stiffness, which could in turn elevate the risk of RRIs. Baltich *et al.* examined the running mechanics with footwear of different midsole hardness (Baltich et al., 2015). They observed an increase in ankle and knee joint stiffness in the softer midsole conditions, suggesting that the increased joint stiffness could give rise to a greater VIP and could subsequently induce bony injuries.

Significantly higher knee stiffness was found in runners suffering from low back pain when compared to the controls and the group with resolved pain, while the ankle stiffness was found to be comparable between the three groups (Hamill et al., 2009). In another study, a trend of higher knee stiffness was observed with moderate effect size (p=0.054, Cohen's d=0.54) in runners with tibial stress fracture when compared to characteristics-matched controls (Milner et al., 2006).

1.3 Reduction of impact loading through gait retraining

1.3.1 Introduction to gait retraining and biofeedback

By identifying possible risk factors of RRIs, runners could recognize the risk they were predisposed to through biomechanical assessments. Corrections and adjustments has to be made in the case of improper running form, and one of the ways to modify gait pattern is through gait retraining (Davis and Futrell, 2016).

Gait retraining, which involves adjusting and re-learning the way an individual stand, walk or run, was first developed for the purpose of rehabilitation. Gait retraining is a form of physical therapy; it helps individual to re-gain the ability for locomotion following an injury or illness. It has been used clinically to correct pathologic gait in individuals with cerebral palsy (Booth et al., 2018), stroke (Teasell et al., 2003) or after joint replacement surgeries (Petersen et al., 2011).

Gait retraining can also be used on runners suffering from RRIs to relieve symptoms or on healthy runners to prevent running injuries. Techniques used often include treadmill training and use of biofeedback. One of the earliest gait retraining study made use of visual feedback to help runners modify their running style (Messier and Cirillo, 1989). The training group received 15 training sessions over a 5-week period, they were shown a recording of their running form and were instructed to modify specific gait parameters prior to each training session. Compared to a control group without receiving any feedback before their sessions, there was significant effect on the training group's running posture. This study showed that gait retraining was effective in altering movement pattern in runners.

1.3.2 Effects of gait retraining on reducing impact loading

The effect of gait retraining does not limit to changes in the movement pattern, but also running kinetics. A number of lab-based gait retraining studies have evaluated different training protocols and their ability to lower the impact loading including VALR, VILR and PPA. Noehren *et al.* reported large effect in the reduction in loading rates (Cohen's *d*=1.1) after runners completed the gait retraining to modify their hip adduction angle (Noehren et al., 2011).

As for healthy runners, Crowell and Davis have also reported reduction in VALR, VILR and PPA with large effect size (Cohen's *d*=1.5-1.7) after gait retraining (Crowell and Davis, 2011). In each of the training, a lightweight accelerometer was affixed on the tibia of the participant, real-time tibial acceleration was shown on a screen with a line making the training target i.e. 50% of the PPA value before training. A similar study that examined the effect of gait retraining on reduction of impact loading was performed in a dual-task condition (Cheung et al., 2018). During the post-training assessment, runners were given a cognitive and verbal counting task while being instructed to run with the modified gait pattern. Distracted runners were able to perform the cognitive task and ran with lowered PPA and loading rates; such findings suggested that runners were in the autonomous stage of motor learning, little cognitive involvement is required to execute the modified gait pattern.

Most of the gait retraining studies reported positive results, yet the sustainability and persistence of these modifications are yet to be determined. Several studies have reported the impact loading during follow-up gait assessments conducted one month after the last training session (Clansey et al., 2014; Crowell and Davis, 2011; Willy et al., 2016). Reduction of impact loading, measured by VALR, VILR or PPA, persisted at the 1-month follow-up with the exception for Clansey *et al.*'s study. In that particular study, PPA, VALR and VILR were all found to be reduced after the training. Although PPA measured at the 1-month follow-up (8.30±1.82 g) was still significantly lower than baseline (10.67±1.85 g), reduction in neither VALR nor VILR could be maintained. Such findings have lead the group into evaluating their feedback strategy in order to optimize retention. Several case studies has included longer follow-up, ranging from 3 months to one year after the training, with the modification maintained (Cheung and Davis, 2011; Davis and Futrell, 2016).

It is important to include follow-up assessments when evaluating the efficacy of gait retraining programs, even by understanding the short-term effect (i.e. 1 month) would be meaningful in further optimizing the protocol. Besides, the practical implication for gait retraining to reduce impact loading is still unexplored. It has been demonstrated by previous studies that gait retraining to reduce loading rate could lower the risk of recurring pain (Cheung and Davis, 2011; Diebal et al., 2012), but the change in risk of RRIs remains unknown (Barton et al., 2016).

1.3.3 Real-time biofeedback and motor skill learning

Feedback provided during gait retraining could be as simple as visual cue by a mirror or verbal cue from the trainers. However, this would limit the type of information that could be given to the runner and is affected by the subjective judgment of the trainer. With the advancement of sensors and motion capture systems, real-time augmented feedback on running kinetics and kinematics could be provided during trainings. It could be a solution to minimize the inconsistency within- and between- runners and trainers, potentially providing a more robust gait retraining protocol.

In the previously mentioned study by Noehren *et al.*, reflective markers were placed on the lower extremities to compute the hip adduction angle in real-time (Noehren et al., 2011), this information together with a normal hip adduction profile were shown to the runners during treadmill training. The trained runners who suffered from patellofemoral pain and showed excessive hip adduction were able to reduce their hip adduction angle after 8 sessions of training.

Real-time biofeedback provided during the gait retraining varied across studies. The method of feedback delivery, including but not limited to visual and auditory feedback were found to be effective in modifying gait patterns (Agresta and Brown, 2015). The type of information provided could be categorized as discrete or in a continuum. Discrete feedback, for example, traffic light colors to indicate high-, moderate- and low-PPA, was found effective in modifying gait kinetics (Clansey et al., 2014). While discrete feedback are more simple and easier to interpret, feedback provided on a continuum, for example, graphs or plots allowed runners to adjust gradually to prevent overshooting, and also allowed them to monitor their progress over time (Crowell et al., 2010).

Another difference in feedback delivery was the amount of feedback given. A fading feedback as compared to a constant feedback provided during all training sessions, was suggested to facilitate motor learning (Winstein, 1991). In the early acquisition phase, guidance in the form of concurrent feedback has been suggested to be effective (Liebermann et al., 2002). After the runner has developed a connection between the feedback provided and internal sensory cues associated with the modified gait pattern, the feedback could be removed in a systemic fashion (Davis and Futrell, 2016). During the transfer phase, a less frequent feedback helps to develop a persistent internal movement pattern, avoiding dependency of the feedback. Such design could optimize performance during retention tests when augmented feedback is not available.

A number of previous gait retraining studies provided feedback information from a single side of two lower limbs (Cheung and Davis, 2011; Clansey et al., 2014; Crowell et al., 2010; Crowell and Davis, 2011; Noehren et al., 2011; Wood and Kipp, 2014). Some studies did not specify the justification for limb selection, while some measured either the symptomatic side (Cheung and Davis, 2011), or the limb with the higher impact loading (Crowell and Davis, 2011). Besides, the evaluation of gait training was based on the training limb only, in which the reported effect could be overstating; as the effect would be greatly compromised if the modified gait fails to be transferred to the untrained limb. The findings in inter-limb skill transfer were not consistent among different studies. Some studies reported unsuccessful inter-limb skill transfer after short-term motor training tasks (Morris et al., 2009; Stöckel and Wang, 2011), while some observed successful skill transfer to the untrained limb (Van et al., 2002). For instance, Krishnan *et al.* (Krishnan et al., 2017) found significant transfer of motor skills from the trained limb to the untrained limb after a gait training. Yet, Choi *et al.* (Choi and Bastian, 2007) suggested that the right and left leg should be trained individually. This research group used a split-belt treadmill to train subjects into walking at different direction and different speed in opposite legs, their results supported the motor adaptation to the new gait was learnt independently for each leg. Moreover, previous studies have reported that injured runners may modify their running mechanics by compensation of the uninjured side in the presence of pain (Noehren et al., 2012a; Tashman et al., 2004a). *Hence, a comprehensive evaluation of the gait training should include both the trained and the untrained side.*

1.4 Footstrike pattern modification

1.4.1 Immediate effect on impact loading

The majority of the distance-running population make initial contact with the ground using the heel (Hasegawa et al., 2007; Larson et al., 2011; Lieberman et al., 2010). In a recent study, 89.6% of the recreational runners were observed to land with a RFS during training (Cheung et al., 2016a). A patented technique, the "Pose Method" have attracted RFS runners to attempt FFS or MFS landing in order to reduce their injury risk and improve their performance (Romanov, 2004).

The effects of acute interventions to alter the footstrike pattern of habitual RFS runners to adopt a non-RFS (i.e. MFS or FFS) landing have been evaluated by several previous studies. A 25.3 to 39.0% reduction of VALR has been reported when habitual RFS runners attempt to run with a MFS (Arendse et al., 2004; Chen et al., 2016; Giandolini et al., 2013). Switching to a FFS could even achieve a greater reduction of VALR by 30.1 to 46.7% (Chen et al., 2016; Shih et al., 2013; Yong et al., 2018), PPA was also found to be reduced by 37.7% (Delgado et al., 2013).

1.4.2 Gait retraining to modify footstrike pattern

Alternation in footstrike pattern has gained popularity for its potential health benefits by lowering impact loading, yet, only a few studies have considered the use of footstrike pattern information as cues for correcting unfavorable gait pattern through retraining (Cheung and Davis, 2011; Diebal et al., 2012; Roper et al., 2016), among which only one has taken impact loading as an outcome variable. The case series (Cheung and Davis, 2011) consists of three female runners suffering from chronic patellofemoral pain. Gait retraining to promote non-RFS landing was found effective in reducing loading rates among the three runners, they were able to reduce the rate of heel strike by 90% after a audio feedback gait retraining; during the trainings, runners were instructed to eliminate buzzer noise by avoiding RFS landing. VALR and VILR were reduced after the training with the footstrike pattern switch and the effects were maintained after 3 months.

1.4.3 Current limitation and future directions

The earlier mentioned gait retraining studies which focused on modification of footstrike pattern were performed on runners who were diagnosed with patellofemoral pain (Cheung and Davis, 2011; Roper et al., 2016) or chronic exertion compartmental syndrome (Diebal et al., 2012). Injured runners experiencing pain might develop antalgic gait, it is unknown whether their motivation to correct their running form and to relieve the pain would affect the outcome of the gait retraining. *There is a lack of evidence to support that similar gait retraining which aims to modify footstrike pattern would be able to reduce impact loading in healthy runners.*

Furthermore, runners were instructed to run with a non-RFS (Cheung and Davis, 2011) or a FFS (Diebal et al., 2012; Roper et al., 2016) instead of a MFS. Although switching to a FFS could reduce loading rates to a greater extend, it might induce an injury risk in the Achilles tendon or triceps surae due to a greater strain (Sinclair, 2014). Therefore, MFS may be a safer option for runners. However the vast number of studies on footstrike pattern transition from RFS to MFS adopted a single-session design. A systematic gait retraining to promote MFS landing therefore requires further investigation.

1.5 Effect of footwear on footstrike pattern and impact loading

Apart from making modifications to the gait pattern through gait retraining, some external factors could also induce changes to the running biomechanics. Surface inclination (An et al., 2015; Gottschall and Kram, 2005), running speed (Keller et al., 1996), running surface (Dixon et al., 2000) and footwear (Clarke et al., 1983; Sinclair, 2017) were all external factors suggested that could affect the footstrike pattern and impact loading.

The cause of an RRI might be manifold, but subjectively, recreational runners considered running shoes as one of the main extrinsic factors that could affect injury risk (Saragiotto et al., 2014). Since runners express great concern about their footwear, different companies have designed cushioning shoe models to soften the impact loading but the effects were equivocal (Reinschmidt and Nigg, 2000). On one hand, biomechanical studies have demonstrated the importance of cushioning. The appearance of the VIP was found to be delayed in shoes with additional cushioning, which would in turn reduce loading rates (Clarke et al., 1983). Another study also compared six different shoe models and reported a higher VILR for the shoes with least cushioning (Dixon, 2008). On the other hand, a softer midsole does not guarantee more protection against impact. Baltich *et al.* conducted a study using footwear with different midsole hardness, they found the highest VIP in the softest midsole, potentially leading to higher VALR and VILR (Baltich et al., 2015). In that particular study, joint stiffness was also measured. An increase in ankle and knee joint stiffness in the softer midsole conditions was observed in the female participants, the combined effect of the joint stiffness could have reduced the overall shock attenuation, which could explain the larger impact loading. Another study found no effect on impact loading, with comparable PPA for midsole thickness from 0 to 16 mm (Chambon et al., 2014).

The contradictory finding could partially be explained by the adaptation in human, McNair and Marshall (McNair and Marshall, 1994) have suggested that the human body would respond accordingly to impact within the "kinetic bandwidth" and therefore the relationship between cushioning and impact loading experienced by runners might not always be linear.

Besides cushioning, the heel-to-toe drop was previously found to alter running biomechanics as well, especially footstrike pattern (Horvais and Samozino, 2013). In some cases, even though a complete transition of footstrike pattern was not observed, a smaller foot-ground inclination angle was found in shoes with a lower heel-to-toe drop, indicating a shift in the direction of a MFS (Chambon et al., 2015; Zhang et al., 2016b). Such changes in footstrike pattern could likely lead to subsequent changes in other running mechanics such as impact loading and joint stiffness.

1.6 Organization of thesis

The methodology of the experiments is presented in Chapter 2. In Chapter 3, an experiment on reduction of impact loading and occurrence of RRI is presented. The findings of this study provide evidence to support the hypothesized biomechanical modification encouraged in the following chapters, leading on to Chapter 4 and 5 by providing evidence on the practical implication of gait retraining. Chapter 4 describes the study assessing the effectiveness of a gait retraining protocol which promotes MFS landing. In addition, the effect on inter-limb skill transfer and sustainability is covered in Chapter 5. Chapter 6 includes results from the extension of the main study presented in Chapter 4 and 5, presenting two experiments on the effect of footwear on footstrike pattern and impact loading. Chapter 7 is the general discussion and conclusion.

1.7 Objectives and hypotheses to be tested

The relationship between impact loading and RRIs has been well-established, and numerous studies have evaluated the efficacy of reducing impact loading through real-time feedback gait retraining. However, it is still plausible that changes to the running biomechanics through gait retraining could prevent RRIs in healthy runners. Moreover, to our best knowledge, there are no studies that have examined the effect of a gait retraining program which promotes MFS on impact loading. Hence, the series of studies in this thesis was designed for a comprehensive evaluation of such a gait retraining program.

1.7.1 Chapter 3

Objective: The purpose of this study was to assess the kinetic change after a lab-based gait retraining program, and the effectiveness in reducing the occurrence of RRI within one year after the training.

Hypothesis: We hypothesized that the loading rates, including VALR and VILR, would be reduced in the trained runners who received feedback during training, but not the control group without feedback. It was also hypothesized that the trained runners would sustain fewer RRIs during the one-year follow-up period when compared with the controls.

1.7.2 Chapter 4

Objective: The purpose of this study was to evaluate the effect of providing footstrike information to runners during gait retraining on footstrike pattern, impact loading and joint stiffness.

Hypothesis: We hypothesized that upon completion of the gait retraining, runners would be able to achieve MFS in the absence of feedback, and subsequently lead to a reduction in VALR and VILR. It was also hypothesized that the ankle and knee joint stiffness would be different after the gait retraining.

1.7.3 Chapter 5

Objective: The purpose of this extension to the study in Chapter 4 was to examine the inter-limb skill transfer by comparing the trained and untrained limb after gait retraining. In addition, we also aimed to assess the sustainability of the effects of the gait retraining after one month.

Hypothesis: We hypothesized that the footstrike pattern and impact loading after the training program would be similar in both the trained and untrained limb. It was also hypothesized that the effect of the training following the retraining program would persist at the one-month follow-up.

1.7.4 Chapter 6

1.7.4.1 Midsole cushioning

Objective: The primary purpose of this study was to compare the footstrike pattern and impact loading in runners with extreme cushioning provided by maximalist (MAX) and conventional footwear (CON) during level and downhill running. The secondary aim was to compare the subjective comfort between the two footwear conditions.

Hypothesis: It was hypothesized that the additional cushioning provided by MAX would promote non-HS (NHS) landing and loading rates would be reduced in both inclination conditions. Additionally, we hypothesized that the comfort rating would be higher in MAX under both conditions.

1.7.4.2 Footwear comfort

Objective: The aim of this study was to use a deceptive study design to investigate the effect of self-perceived footwear comfort on running biomechanics. The subjective comfort and running biomechanics were measured and compared between the same pair of shoes described differently in the design and cost.

Hypothesis: It was hypothesized that there would be a within-subject difference in the comfort perception, but no within-subject differences in running biomechanics when running in the same pair of shoes.

CHAPTER 2

METHODOLOGY

2.1 Marker model for measuring footstrike angle

The marker model used for measuring the footstrike angle (FSA) was based on a previous study (Altman and Davis, 2012). Two reflective markers, HEEL and TOE, were placed on the runner's shoe at the calcaneus and the second metatarsal head (Figure 2.1). Three-dimensional marker positions captured through the motion capture system (Vicon, Oxford, UK) were used to compute the FSA.

The FSA was calculated as the angle between the foot and the running surface in the sagittal plane at IC. In order to ensure repeatability and compensate the variance in marker placement, an offset angle was taken before the running trials for studies in Chapter 4-6. The angle between the line joining the two markers and the ground while the participant was standing naturally was recorded as the offset angle. This offset was subtracted from the FSA during the running trials. An inclined foot with the metatarsus higher than the heel is indicated by a positive FSA. The cut-off between the three footstrike patterns was shown in Figure 2.2.

Figure 2.1 Reflective marker positions for HEEL and TOE

Figure 2.2 Classification of footstrike pattern based on footstrike angle (FSA) during initial contact

2.2 Marker model for lower-limb kinematics

Marker trajectories and kinetics data collected through the motion capture system and the instrumented treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) were used to process the lower-limb kinematics and kinetics. A validated lower-body Plug-In Gait model (Vicon, Oxford, UK) made use of subject-specific limb anthropometry data, body mass and height to compute required joint kinematics and kinetics, including ankle, knee and hip joint angles and moments (Kadaba et al., 1989; Winter, 2009).

The validated model made use of sixteen reflective markers that were placed over specific anatomical landmarks in the lower body. The markers were placed on both the left and right sides, the positions were tabulated in Table 2.1 and illustrated in Figure 2.3.

Table 2.1 Reflective marker positions for lower-body model

Left and right	**Position**
Anterior superior iliac spine	Anterior superior iliac spine
Posterior superior iliac spine	Posterior superior iliac spine
Thigh	Lateral surface of the thigh
Knee	Lateral femoral epicondyle
Shank	Lateral surface of the shank
Ankle	Lateral malleolus
Toe	Second metatarsal head
Heel	Calcaneus

Figure 2.3 Reflective marker positions for the lower-body model

2.3 Vertical loading rates measurement

The calculation of VALR and VILR was briefly described in section 1.2.1. The GRF is the resultant force exerted by the ground onto the body in contact with it, and could be separated along three axes, namely medial-lateral, anterior-posterior and vertical.

The vertical component of the GRF between the initial foot-ground contact and the moment the same foot leaves the ground was used to compute the vertical loading rates. Referring to a previous study (Crowell et al., 2010), a VIP was identified from the vertical GRF-time curve as the local maximum within the first 50 ms of foot-ground contact. In the event of an undetectable VIP, the force value at 13% stance phase was used as a substitute of the VIP value (Blackmore et al., 2016).

The linear portion between the 20% and 80% point of the VIP value was defined as the region of interest (Figure 2.4). The slope of the line joining the 2 points was calculated as the VALR, and the maximum difference between successive points within the region of interest was calculated as the VILR.

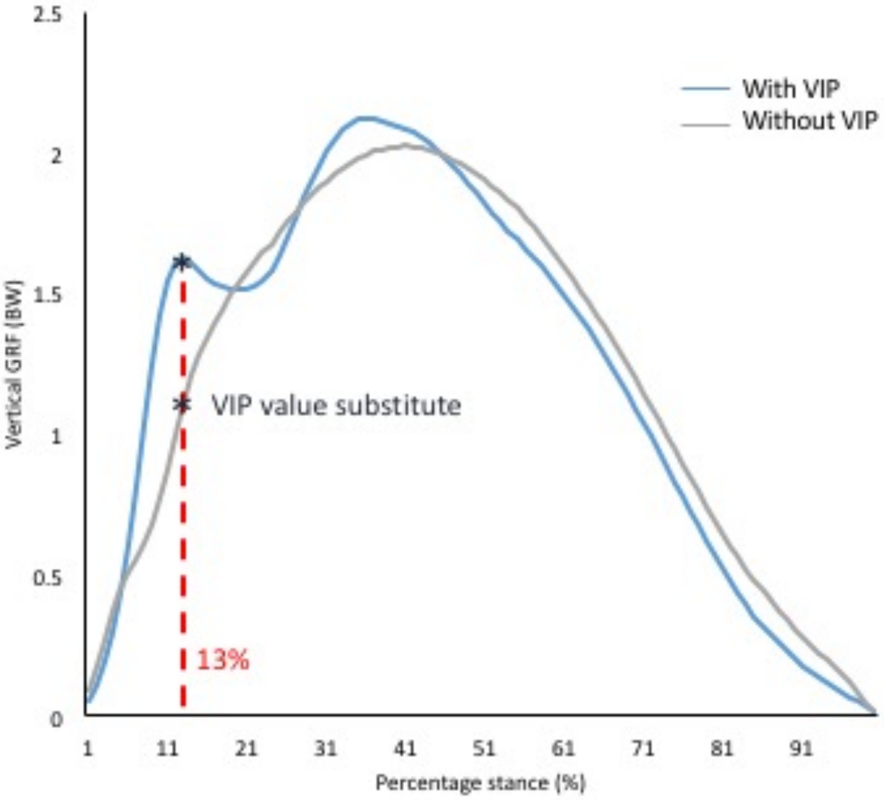

Figure 2.4 Vertical ground reaction forve curve illustrating the vertical impact peak substitute value at 13% stance phase in the case of undetectable vertical impact peak

GRF, Ground reaction force; BW, Bodyweight; VIP, vertical impact peak

2.4 Gait retraining protocol

All gait retraining sessions (Chapter 3-5) were conducted on an instrumented treadmill at the Gait and Motion Analysis Laboratory of the Hong Kong Polytechnic University.

The gait retraining program, which was previously established and evaluated in previous studies (Cheung et al., 2018; Crowell and Davis, 2011; Noehren et al., 2011) involves 8 sessions, with training time gradually increasing from 15 to 30 minutes (Figure 2.5). In the first four sessions, feedback was provided all through the training. In the remaining four sessions, feedback was gradually taken away, participants were provided with feedback only in the beginning and end of each training session. Participants were encouraged to maintain the modified gait pattern during the time when feedback was not available.

The whole training was separated into two phases, the acquisition phase and the transfer phase. Reviews on motor control principles and gait retraining suggested that this training schedule could facilitate the learning of a new motor program and enhance retention (Davis and Futrell, 2016; Sigrist et al., 2013; Winstein, 1991). During the acquisition phase, runners require cues constantly to develop a connection between the external and intrinsic feedback (Davis and Futrell, 2016). Concurrent feedback attracts a runner’s external focus of attention and was found to be beneficial in promoting internalization of the movement, and is therefore considered optimal in this stage (Shea and Wulf, 1999; Sigrist et al., 2013). After the link between the external feedback and the proprioception of the runner has been established, external feedback could be removed gradually. The fading feedback could avoid dependency and prevent runners from over-relying on the feedback.

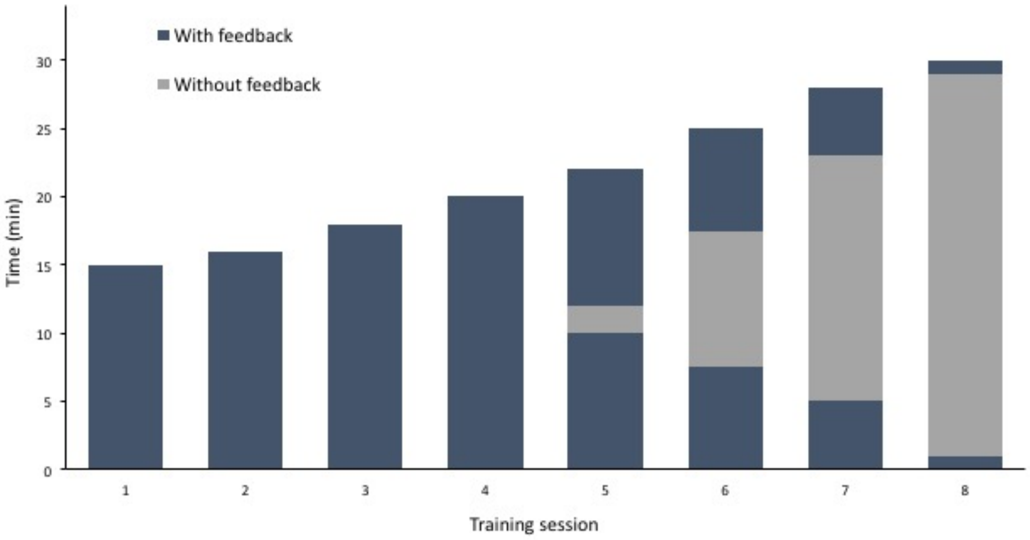

Figure 2.5 Training time and feedback time arrangement for the 8-session gait retraining program

CHAPTER 3

EFFECT OF GAIT RETRAINING ON RUNNING INJURY RISK

3.1 Introduction

Distance running has gained popularity both globally and locally. The trend in Hong Kong could be reflected by the increasing number of runners participating in various local running events held throughout the year. The Hong Kong Standard Chartered Marathon has been one of the most well-known road running events. The number of competitors has surged in the past twenty years, from 1,076 in 1997 to a record-breaking 73,395 in 2017 (*2018 Standard Chartered Hong Kong Marathon - Marathon Race Handbook*, 2018). There were a number of health benefits found to relate to running, however, novice runners who just started their training might not realize the high injury risk that came with the physical exercise they were engaged in. A review on incidence of RRIs has reported a weighted estimate of 7.7 RRIs per 1,000 hours of running in recreational runners, and the rate was even more alarming in novice runners, with up to 17.8 RRIs per 1,000 hours of running (Videbæk et al., 2015). With up to 85% of novice runners incurring an injury every year (Kluitenberg et al., 2015), it is important to identify the risk factors of injury and prevent its development.

The development of an RRI was considered multi-factorial; internal and external risk factors interacting with one another and collectively predisposed certain runners to a higher risk of injury (van der Worp et al., 2015; van Gent et al., 2007). Among these factors, high impact loading has been suggested to be related to the development of RRIs (Davis et al., 2016). The relationship between impact loading and injury has been demonstrated in animals models, mostly rabbits (Archdeacon et al., 1996; Radin et al., 1978; Serink et al., 1977). Impact loading was often measured as VALR and VILR in human, and retrospective studies has reported strong association between high VALR and VILR with RRIs, such as patellofemoral pain (Cheung and Davis, 2011), tibial stress fractures (Pohl et al., 2008) and plantar fasciitis (Pohl et al., 2009). Clinically, various approaches have been attempted to reduce the impact loading in runners, aiming to prevent RRIs, such as cushioning running shoes (Barnes and Smith, 1994; Sinclair, 2017), altering running posture using coach-based training programs (Arendse et al., 2004; Dreyer and Dreyer, 2009; Romanov and Robson, 2004); however, the efficacy of these interventions were not supported by existing evidence.

It has been proposed that reduction of impact loading could be achieved through modification to the running pattern with the help of real-time feedback (Crowell et al., 2010; Davis and Futrell, 2016). Runners could go through supervised gait retraining programs to correct their improper running pattern, and various training protocols were found to be effective in reducing impact loading (Agresta and Brown, 2015; Cheung and Davis, 2011; Crowell and Davis, 2011). The gait retraining program used in a previous study involved eight training sessions organized within two weeks, each of fifteen to thirty minutes (Crowell and Davis, 2011). Runners were informed about the target of the training, i.e. reduce impact loading, before the first session, and during the training, real-time feedback was provided to help the runners to maintain the desired gait pattern. This group of trained runners were able to reduce their VALR and VILR for over 32% when the feedback was removed after the training, and such reduction could be maintained after one month. The participants of these studies were mostly experienced runners (Crowell and Davis, 2011), while some even sustain an RRI (Cheung and Davis, 2011; Noehren et al., 2011), *there is a lack of evidence to support that novice runners at high risk of injury could also benefit from gait retraining.*

Moreover, although most of the gait retraining studies reported positive results for reduction in impact loading, it is still unknown whether such changes would affect the injury risk in runners. There has not been a published study that examined the effect of a gait retraining to reduce impact loading on the injury prevalence in runners. *A knowledge gap between the effect of gait retraining to reduce impact loading and the association between impact loading and injury risk still exists.*

Hence, this randomized controlled trial (RCT) aimed to examine the impact loading before and after the gait retraining in a group of novice runner. We also evaluated the effectiveness of the program on the annual incidence of RRI.

3.2 Methods

3.2.1 Participants

The sample size required was calculated based on the annual occurrence of RRIs. According to previous studies, the annual occurrence of RRI ranged between 37% and 79% (Lun et al., 2004; van Gent et al., 2007). A reduction of 25% in the annual occurrence in the intervention group compared to the control group was regarded as clinically significant according to a previous RCT (Bredeweg et al., 2012). A logistic regression survival power analysis was conducted based on a 25% reduction in annual occurrence of injury, an 5% attrition rate, a significance level of 5% and power of 80%; it was determined that 380 runners were required to detect an effect on our intervention.

Novice runners were recruited from a number of local running clubs through coaches. The inclusion criteria were as follows: 1) less than two years of running experience, 2) average weekly mileage of more than 8 km, and 3) within the age of 18-50. Participants were excluded if they sustain an RRI in the past six months or any musculoskeletal conditions that would affect their running gait. Each participant gave informed consent prior to participation according to an approved protocol reviewed by the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University.

Twenty-two runners were excluded from the allocation process based on the selection criteria, details shown in Figure 3.2. The remaining 390 participants were being assigned into the intervention group (Gait retraining) and the control group after the Pre-training evaluation. To prevent an imbalance of participant characteristic between groups which would potentially influence the outcome, all participants were first grouped into 6 strata based on gender and current training volume (weekly mileage: 8-12 km, 12-16 km and >16 km). Within each stratum, a block randomization with a block size of four was used to assign participants into the Gait retraining group and the Control group.

320 participants completed the whole experiment, including Pre- and Post- training assessments, all training sessions and the one-year follow-up. The mean and SD (standard deviation) of the characteristics for both groups are presented in Table 3.1.

3.2.2 Biomechanical data collection

All participants underwent an instrumented running assessment before group allocation. They were given five minutes to warm-up on an instrumented treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) in their self-selected speed (Wood and Kipp, 2014). After a five-minute rest, they returned to the treadmill for two five-minute running trials in two testing speeds: 8 km/hr and 12 km/hr, separated with a five-minute rest period. The sequence of the speed was randomized by an online program (https://www.random.org/). GRF data was sampled at 1,000 Hz through the instrumented treadmill during the last minute of each running trial.

Both groups of runners returned to the laboratory on the following day after their last training session, a Post-training assessment with identical setup and procedure as the Pre-training assessment was conducted. Participants wore their own running shoes, and the same pair was used for both assessments and throughout the training sessions.

Table 3.1 Characteristics of the participants in the Gait retraining and the Control group

Characteristics	**Gait retraining** **(n=166)**	**Control** **(n=154)**
Gender	82 males, 84 females	76 males, 78 females
Age (year)	33.6±9.5	34.2±9.5
Weight (kg)	60.0±12.6	61.6±12.0
Height (m)	1.66±0.09	1.65±0.09
Weekly mileage (km)	19.5±7.0	18.5±6.1
Running experience (year)	1.40±0.43	1.38±0.42

3.2.3 Training protocol

The lab-based gait retraining was conducted on the instrumented treadmill in the Gait and Motion Analysis Laboratory of the Hong Kong Polytechnic University. The training was conducted over two weeks according to a training schedule previously established and detailed in section 2.4 (Crowell and Davis, 2011). Each participant had his/her own training speed which was kept constant throughout the eight sessions; the speed was set to match with their usual training speed.

For the Gait retraining group, participants were shown two GRF curves samples, with and without VIP, before they start the training. They were instructed to soften their footfalls so as to reduce the VIP within the vertical GRF curve. During the training, vertical GRF from the instrumented treadmill was displayed using a customized LabVIEW (National Instruments, Austin, TX, USA) program; the x-axis was scaled as 400 ms and y-axis as 3 times of participants' body weight. The visual feedback was provided on the monitor placed in front of the treadmill (Figure 3.1).

Participants in the Control group were also invited back to the laboratory after the Pre-training assessment. They completed eight treadmill running sessions on the instrumented treadmill, the training schedule was identical to the Gait retraining group, but visual feedback was not provided to this group of participants.

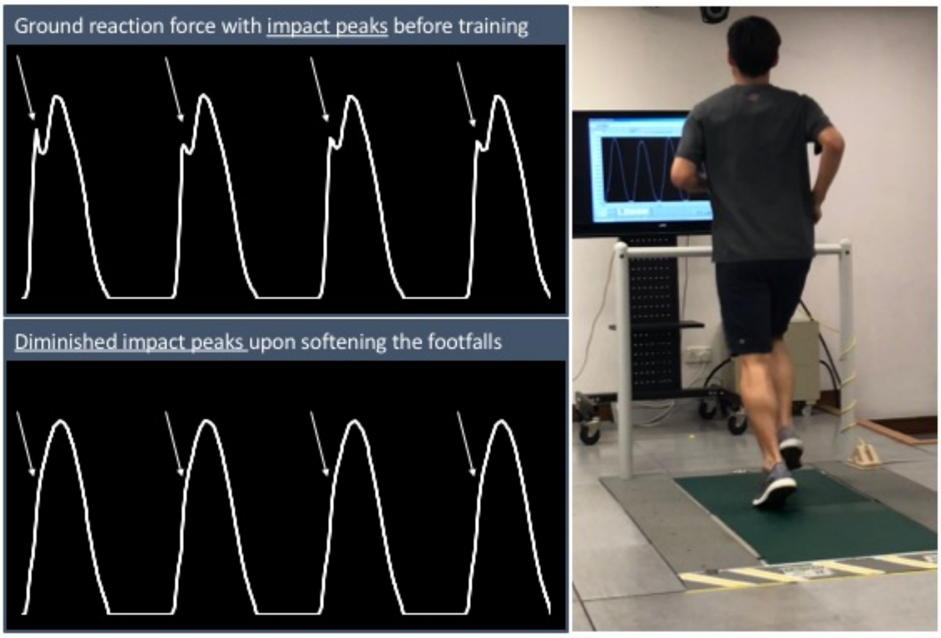

Figure 3.1 Real-time ground reaction force curve shown to the participants during training. They were asked to soften the footfalls to reduce the amplitude of the vertical impact peaks.

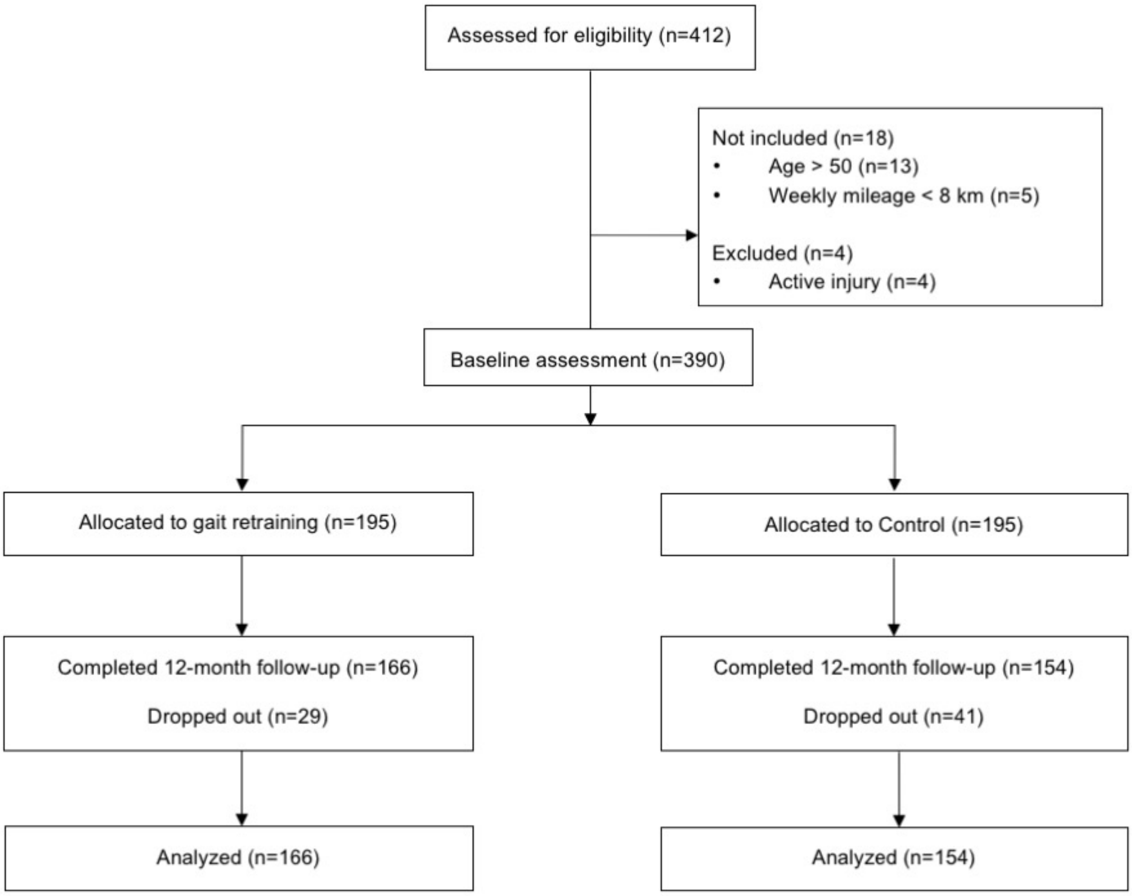

Figure 3.2 CONSORT flow diagram

3.2.4 Injury surveillance

Both groups of participants were required to report their monthly running log and injury profile using an online survey platform (Google Forms, Google, Menlo Park, CA, USA). The monthly survey was designed based on a previous study (Altman and Davis, 2016), participants were required to complete the survey for twelve consecutive months. Monthly reminders were automatically sent to each participant every month through E-mail. The survey recorded their training volume and whether they were affected by any RRI in the past month. For injured runners, information regarding their RRI including the date of injury, affected side and diagnostic procedure were recorded as well (Appendix I).

For this study, the definition of an RRI was based on a previous large-scale study (Taunton et al., 2002). Any musculoskeletal pain or symptoms which caused the participant to miss two or more days of training and was diagnosed by a medical professional would be considered as a RRI. In order to ensure validity of the participant-reported condition, a researcher contacted all participant who reported a RRI to verify the incident and confirmed the record.

3.2.5 Biomechanical data analysis

Based on the procedures described in a precious study to obtain VALR and VILR (Davis et al., 2016), kinetics data were filtered by second-order Butterworth low-pass filter with a cut-off frequency of 50 Hz. A cut-off threshold of 10 N was used to identify the IC and toe-off (Crowell et al., 2010; Davis et al., 2016). VALR and VILR for both testing speeds were computed based on the procedure described in section 2.3. VALR and VILR were averaged across all footfalls within the one-minute data collection, and were normalized to participant's body weight.

3.2.6 Statistical analysis

Characteristic of the participants, VALR and VILR in both speeds during Pre-training assessment between the Gait retraining group and the Control group was compared using independent *t*-tests, gender distribution was compared using Chi-square test. 2 x 2 mixed model ANOVAs were used to compare the interaction effect of training (between-subject factor: Gait retraining group and Control group) and time (within-subject factor: Pre- and Post-training) on all four dependent variables, VALR and VILR at two testing speeds. Pairwise comparisons were conducted in the case of significant interaction. Cohen's *d* was calculated for effect size. The global level of significance for all statistical calculations was set at 0.05.

The data collected from the monthly surveys were reduced to the number of injured and non-injured runners for each month after the training. The first RRI of each participant was considered the "endpoint" in the survival analysis. Mantel-Cox test was used to compare the survival curves of the participants between the intervention group and the control group. A Cox proportional-hazards regression was conducted to assess the difference in injury occurrence within twelve months.

The global level of significance for all statistical calculations was set at 0.05. Statistical tests were computed using SPSS for Windows, Version 22 (SPSS, Inc., Chicago, IL, USA). Effect size was calculated by G*POWER 3.1 (Universität Kiel, Germany).

3.3 Results

There was no between-group difference found in the participants' characteristic (*p*>0.172) and Pre-training loading rates (*p*>0.094). A CONSORT diagram (Figure 3.2) shows the number of drop-outs and the total number of participants in each group.

According to the results of the 2 x 2 mixed model ANOVA, significant interaction effects between the training and time was observed in both VALR ($p<0.001$, $\eta_p^2>0.344$) and VILR ($p<0.001$, $\eta_p^2>0.353$) at both 8 km/hr and 12 km/hr.

Results of the pairwise comparisons for the effect of training on the Gait retraining group are presented in Table 3.2. Significant reduction in VALR and VILR were observed in both testing speeds for the Gait retraining group. No significant difference was found in VALR and VILR at 8 km/hr between Pre- and Post-training in the Control group, but VALR and VILR at 12 km/hr were both found to be significantly higher in the Post-training assessment (p<0.029, Cohen's *d*=0.09-0.14).

For between-groups comparisons, VALR and VILR in both testing speeds during Post-training were significantly lower in the Gait retraining group as compared to the Control group (p<0.001, Cohen's d=1.16-1.52). All pairwise comparisons with significant different either between-groups or within-groups are shown in Figure 3.3.

The proportion of injured and non-injured runners were summed up for the whole injury surveillance period, 16% and 38% of participants reported RRIs in the Gait retraining and the Control group respectively. Injury pattern for the two groups are presented in Figure 3.4. Mantel-Cox test revealed a significant difference in the survival curves between the intervention group and the control group (Figure 3.5). The hazard ratio calculated from the Cox proportional-hazards regression was 0.38, which indicated a 62% lower RRI occurrence in the Gait retraining group compared with the Control group.

Table 3.2 Vertical average and instantaneous loading rates for the intervention group before and after the training

Gait retraining group				
	Pre-training	**Post-training**	***P*-value**	**Cohen's *d***
VALR at 8 km/hr (BW/s)	65.95±9.90	54.82±11.04	<0.001	1.06
VILR at 8 km/hr (BW/s)	90.69±13.90	75.01±17.10	<0.001	0.99
VALR at 12 km/hr (BW/s)	81.28±13.59	66.65±12.53	<0.001	1.17
VILR at 12 km/hr (BW/s)	111.87±14.51	94.75±19.61	<0.001	0.97

VALR, Vertical average loading rate; VILR, Vertical instantaneous loading rate; BW, Bodyweight

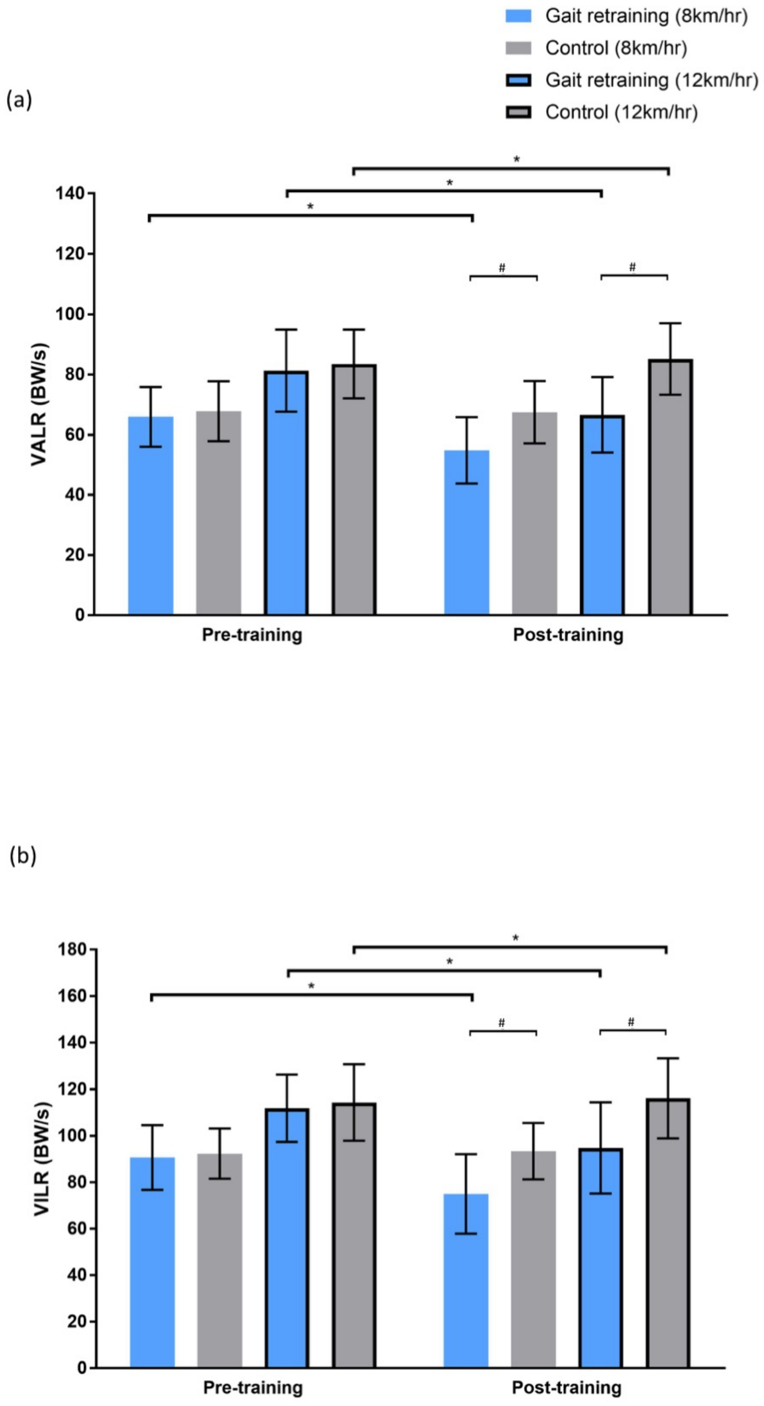

Figure 3.3 Vertical average (a) and instantaneous (b) loading rates before and after retraining for the Gait retraining group and the Control group
BW, body weight
# *P*<0.05, pairwise comparison between groups (Gait retraining and control group)
* *P*<0.05, pairwise comparison within groups (Pre- and Post-training)

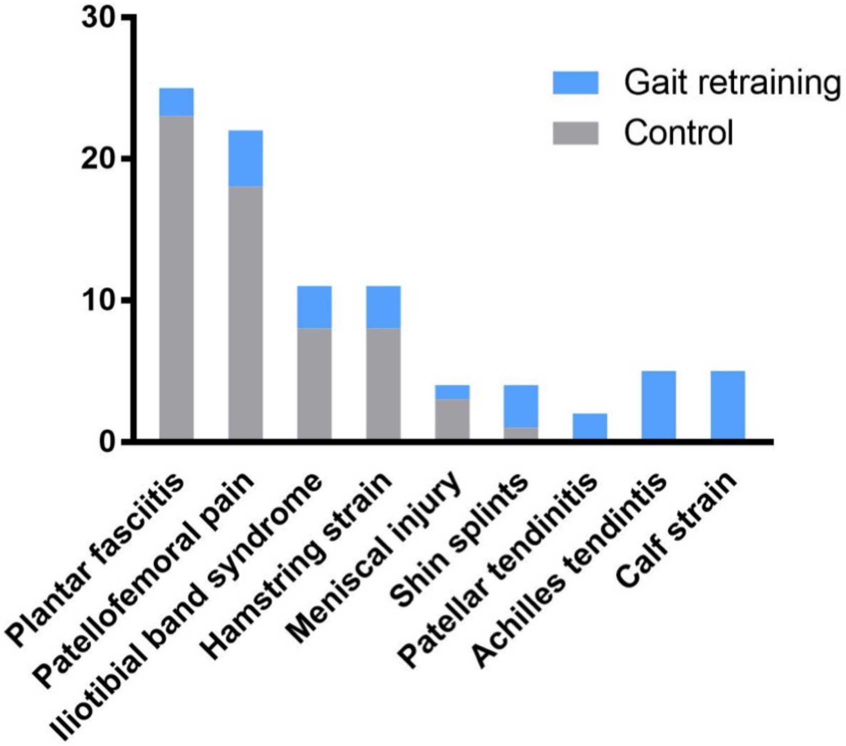

Figure 3.4 Frequency of running-related injuries experienced by Gait retraining and Control groups

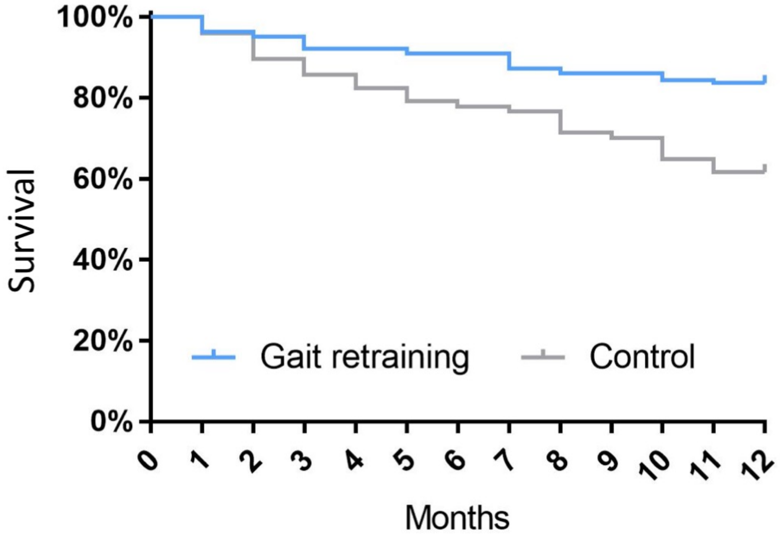

Figure 3.5 Kaplan-Meier curves of running-related injury between participants for the gait retraining and control groups

3.4 Discussion

The purpose of this RCT was to evaluate the effectiveness of a gait retraining program which promoted softer landings on reduction in loading rates and reducing injury occurrence within a twelve-month follow-up period. Based on the biomechanical analyses, the Gait retraining was effective in reducing the VALR and VILR. More importantly, results of this study suggested that the gait retraining program was able to reduce the occurrence of RRI. The trained runners experienced 62% less injuries than the control group during the twelve-month follow-up.

Based on findings of previous gait retraining studies to reduce impact loading (Cheung and Davis, 2011; Crowell and Davis, 2011), we hypothesized that participants would be able to run with lower VALR and VILR after the 8-session gait retraining. Results of this study supported this hypothesis, reductions of 15.3-18.0% were observed in the VALR and VILR within the intervention group. A value of 66.0 BW/s was previously used as a cut-off to categorize VALR value as low or high based on a retrospective study identifying biomechanical factors associated with tibial stress fractures (Milner et al., 2006). In a previous prospective study which examined the relationship between RRIs and loading rates in a group of female runners, for runners with a high VALR (> 66.0 BW/s), the odds ratio of sustaining a RRI that required medical attention was found to be 2.72 (Davis et al., 2016). In the present study, the Post-training VALR at 8 km/hr and 12 km/hr were reduced to a value of 54.82 and 66.65 BW/s respectively. It has previously been demonstrated that the value of VIP increases with running speed between 10.8 and 20.8 km/hr (Nigg et al., 1987), and loading rates would likely follow a similar trend. The Post-training VALR at 12 km/hr in our study among trained runners was slightly above 66.0 BW/s, it is reasonable to assume that runners were able to run within a safe zone in their regular training speed (8-12 km/hr).

We mainly referred to the gait retraining protocols used in previous studies, with some modifications to promote the training sustainability. For instance, the assessment and training speed was set to match each participant's usual training speed. As speed was found to affect the magnitude of loading rates (Keller et al., 1996; Nigg et al., 1987), a training conducted at the speed of participants' usual training speed would minimize the effect of speed change and compromise the effectiveness of the gait retraining during the follow-up period. Participant also wore their own usual running shoes for the same purpose, as footwear was also found to affect loading rates (Chambon et al., 2014; Milani et al., 1997). Another modification was the feedback provided. The visual feedback was not limited to a single side, GRF was a continuous measurement between the runner and the treadmill, a GRF curve in the shape of an inverted "V" would be shown for every footfall, including both left and right. Runners in the Gait retraining group would be able to modify both limbs during the training, unlike previous studies that displayed the PPA or hip angles from a single side (Crowell and Davis, 2011; Noehren et al., 2011). RRIs could happen to both sides of the human body, it is reasonable for our assessments to be based on both sides, which could better reflect the effectiveness of the training.

Runners were instructed to run with softer landings, but were not given further instructions or strategies that could help them achieve this target. Runners were encouraged to explore various techniques on their own, this would ensure a more natural gait pattern within the physical ability of the runner. In this study, participants were provided with vertical GRF, this type of feedback was considered external. Internal focused feedback, for example specific movement patterns, were found to have a detrimental effect on skill learning (Wulf et al., 2010). Externally focused feedback was shown to have better outcome in terms of retention when compared with internal focused feedback (Shea and Wulf, 1999; Wulf et al., 2010). This design was also to ensure sustainability of the modified gait during the follow-up period. Although we did not collect data during the training session, we observed some common strategies adopted by runners to soften their footfalls, which included switching to a MFS or FFS and shortening their stride length. These biomechanical changes were previously found to be effective in reducing impact loading in runners (Arendse et al., 2004; Chen et al., 2016; Mercer et al., 2002).

We found a significantly lower injury occurrence in the Gait retraining group as compared to the control, this supported our hypothesis in the use of gait retraining to prevent injury. This finding is of practical significance, as RRI was shown to put a huge health and economic burden on the running population (Hespanhol Junior et al., 2016). The risk of RRIs was up to 79% for a given year (Lun et al., 2004; van Gent et al., 2007), an effective intervention for injury prevention was therefore in great demand.

It is important to note that trained runners were not free from RRIs, while the number of patellofemoral pain and plantar fasciitis, injuries that were previously found to be associated with high impact loading (Cheung and Davis, 2011; Pohl et al., 2009), reported by the Gait retraining group was lower than the control group, we observed a higher rate of Achilles tendinitis and calf strain. These calf injuries could be a result of greater stain when participants modify their gait. A greater Achilles tendon force was found in runners who switched to a FFS (Roper et al., 2016). In Crowell and Davis' gait retraining to reduce PPA, a sub-group of runners also reported soreness in their calves within the training. Further study could investigate the different strategies adopted by runners to reduce impact loading and differentiate the injury pattern between various methods, this could allow runners and clinicians to design subject-specific gait retraining, accounting for the variance between runners.

3.5 Conclusion

In conclusion, a two-week gait retraining program was found effective in reducing impact loading in novice runners. Such biomechanical changes in the modified gait pattern within the trained runners were also found to reduce injury occurrence by 62%, as compared to the control group.

3.6 Funding support

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CHAPTER 4

IMMEDIATE EFFECT OF GAIT RETRAINING TO PROMOTE MIDFOOT LANDING PATTERN ON IMPACT LOADING AND JOINT STIFFNESS

4.1 Introduction

Recreational running is one of the most popular activities across the world but unfortunately, is accompanied by a high prevalence of RRIs. Specifically, research has reported the incidence of an RRI within a year can be as high as 79% (Lun et al., 2004; van Gent et al., 2007) with an injury risk of up to 12 RRIs per 1,000 hours of running (Bovens et al., 1989). Among RRI risk factors such as injury history, training errors, and anthropometry (Hreljac, 2005), a considerable amount of research has been focused on different biomechanical gait variables. In chapter 3, a RCT which investigated the relationship between impact loading and the occurrence of RRIs prospectively has been presented. Participants in that particular RCT completed 8 sessions of gait retraining to soften their footfalls, the impact loading was reduced by 15.3 – 18.0% among the trained runners, and a 62% lowered injury risk was observed when compared to the control group. This study provided evidence and set an example in support of gait retraining to reduce injuries in distance runners.

Throughout the years, various lab-based gait retraining studies have evaluated different training protocols and their effectiveness to lower the impact loading including VALR and VILR. Different groups of researchers including Noehren *et al.* and Crowell and Davis, were able to demonstrate significant reduction in VALR and VILR upon training (Crowell and Davis, 2011; Noehren et al., 2011). These studies made use of various types of biofeedback to help runners reduce their impact loading, most of which used feedback that was directly related to the magnitude of impact force.

Another contributing factor of RRIs is the footstrike pattern. The three types of footstrike pattern are RFS, MFS and FFS, classification was based on the location of the center of pressure with respect to the foot section at IC (Cavanagh and Lafortune, 1980). Manipulation of the footstrike pattern has gained popularity recently. Potential health benefits has been suggested for its effect in lowering the impact loading (Lieberman et al., 2010), yet, only a few studies have considered the use of footstrike pattern information as feedback for correcting gait pattern through retraining, among which only one has taken impact loading as an outcome variable (Cheung and Davis, 2011; Diebal et al., 2012; Roper et al., 2016). In the mentioned studies, habitual RFS runners adjusted their footstrike pattern to non-RFS, mainly FFS. Finding suggested that gait retraining is favorable in managing pain in injured runners, improving performance and reducing impact loading. However, switching to a FFS is not without cost. Despite switching to a FFS could reduce loading rates, it remains debatable among researchers whether a switch to FFS should be encouraged (Hamill and Gruber, 2017). Roper *et al.* has reported incidence of ankle pain for two out of eight runners who converted their footstrike pattern from RFS into FFS, suggesting the increased Achilles tendon force be the reason behind the pain (Roper et al., 2016).

Running with a MFS, therefore, might mediate between the two extremes by reducing the impact loading without over-straining the Achilles tendon. Different acute interventions to alter the footstrike pattern of habitual RFS runners to adopt a MFS landing have been evaluated. Methods including a Pose method training (Romanov and Robson, 2004) and visual or verbal cues were found effective in reducing loading rates, with reduction ranging between 25 and 39.0% (Arendse et al., 2004; Chen et al., 2016; Giandolini et al., 2013). *However, effects of a systematic gait retraining to promote MFS landing on the biomechanics in distance runners has yet been examined.*

Biomechanical analyses of various footstrike patterns suggested that the difference in loading rates was likely coupled with a re-organization of the control strategy of joints, resulting in different strategies of shock attenuation (Hamill et al., 2014; Laughton et al., 2003). Specifically, the ankle joint stiffness was found to be reduced when habitual RFS runners ran with a FFS, while the knee joint stiffness displayed an opposite trend (Hamill et al., 2014). Both ankle and knee joint stiffness contributes to the lower extremity stiffness, which was suggested to play an important role in both injury development and running performance (Butler et al., 2003). Therefore, it is important to understand how footstrike pattern change may affect the ankle and knee joint stiffness, and *currently, most studies investigated the joint stiffness change between RFS and FFS, it is still not clear how switching to a MFS would alter the joint stiffness.*

Hence, the purpose of this study was to evaluate the effect of providing footstrike information to runners during gait retraining on footstrike pattern, impact loading and joint stiffness. It was hypothesized that upon completion of the gait retraining, runners would be able to achieve MFS in the absence of feedback, and subsequently lead to a reduction in VALR and VILR. Based on the hypothesis of the change in footstrike pattern, changes in the ankle and knee joint stiffness after the training were also hypothesized. A secondary aim of the study was to better understand the mechanism behind the hypothesized biomechanical changes. The changes in footstrike pattern and joint stiffness were compared against the change in impact loading for possible relationship.

4.2 Methods

4.2.1 Participants

An *a priori* power analysis was conducted using G*POWER 3.1 (Universität Kiel, Germany) to determine the sample size needed for the present study. The calculation was based on the preliminary data collected from a pilot test performed on 5 runners; the primary variables of interest included FSA and VALR. With significance level (α) of 0.05 and power (1-β) of 0.80, the estimated sample size was 7 and 10 for FSA and VALR respectively. In order to account for the potential attrition rate of 10%, at least 12 participants were required for this study.

Male recreational runners were recruited from local running clubs. The inclusion criteria were as follows: 1) at least two years of running experience, 2) average weekly mileage of more than 15 km in the past six months, and 3) landing with RFS habitually (described in section 4.2.2). Participants were excluded if they sustain an RRI or any musculoskeletal conditions that would affect their running. Each participant gave informed consent prior to participation according to an approved protocol reviewed by the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University.

The mean and SD of the characteristics of the fourteen participants meeting the selection criteria are presented in Table 4.1.

Table 4.1 Characteristics of the participants

Characteristics	Mean and SD
Age (year)	39.4±5.8
Weight (kg)	71.2±6.3
Height (m)	1.76±0.07
Weekly mileage (km)	34.1±12.9
Running experience (year)	5.0±3.4

4.2.2 Initial screening

An initial screening was set to ensure all participants land on their heels naturally. Two retro-reflective markers (HEEL and TOE) were placed onto the right calcaneus and second metatarsal head over the shoe of the participant, according to Altman and Davis's model detailed in section 2.1 (Altman and Davis, 2012). The treadmill speed was set to match each participant's regular training speed. Following five minutes of warm-up (Wood and Kipp, 2014), kinetic data and marker trajectories were sampled for one minute at 1,000 Hz and 200 Hz respectively. Kinetic data was sampled through the instrumented treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA), while marker trajectories were recorded using an 8-camera motion capture system (MX, VICON, Oxford, UK). Runners who used a RFS (FSA greater than 8°) over 90% of all footfalls were included in this study.

4.2.3 Data collection

All participants underwent running biomechanics assessments before (Pre) and after (Post) the gait retraining program. The Pre-training data was collected one day before the first session of training, and the Post-training data was collected on the next day after the last session. Each participant wore the same pair of shoes throughout the experiment. In order to obtain lower-limb kinematics, sixteen retro-reflective markers were affixed by a single researcher over specific anatomical landmarks based on the validated model described in section 2.2 (Kadaba et al., 1989; Winter, 2009). The knee and ankle width of both limbs were measured by an anthropometer (Anthroflex small bone anthropometer, NutriActiva, MN, USA) and was recorded together with the leg length of each participant.

After subject preparation and collection of anthropometry data, participants performed a five-minute warm-up on the instrumented treadmill. The treadmill speed and data collection setup were identical to the initial screening, kinetics and kinematics data were collected for one minute.

4.2.4 Training protocol

The lab-based gait retraining was conducted on the instrumented treadmill in the Gait and Motion Analysis Laboratory of the Hong Kong Polytechnic University. The training was conducted over two weeks according to a training schedule previously established and detailed in section 2.4 (Crowell and Davis, 2011). The training speed was the same as the testing speed, and kept constant during the eight sessions. Participants were instructed to modify their footstrike and maintain a MFS pattern with the help of the feedback.

The right side was selected for training. Real-time footstrike information of the training limb was displayed on a monitor placed in front of the treadmill, as shown in Figure 4.1. During the training, three-dimensional marker location of the HEEL and TOE were streamed from the motion capture system to MATLAB (The MathWorks, Inc, Natick, MA, USA). FSA of the training limb was computed by customized MATLAB codes and real-time footstrike information was displayed. The visual feedback comprised of a graphical display of the type of footstrike and a 3-letter label (RFS, MFS or FFS).

In addition to the model used to compute FSA, three additional reference markers were affixed onto the lateral malleolus, lateral surface of the shank and lateral femoral epicondyle of the training limb (Figure 4.2). The three markers were used to optimize the auto-tracking performance by allowing the motion capture system to identify the HEEL and TOE markers accurately.

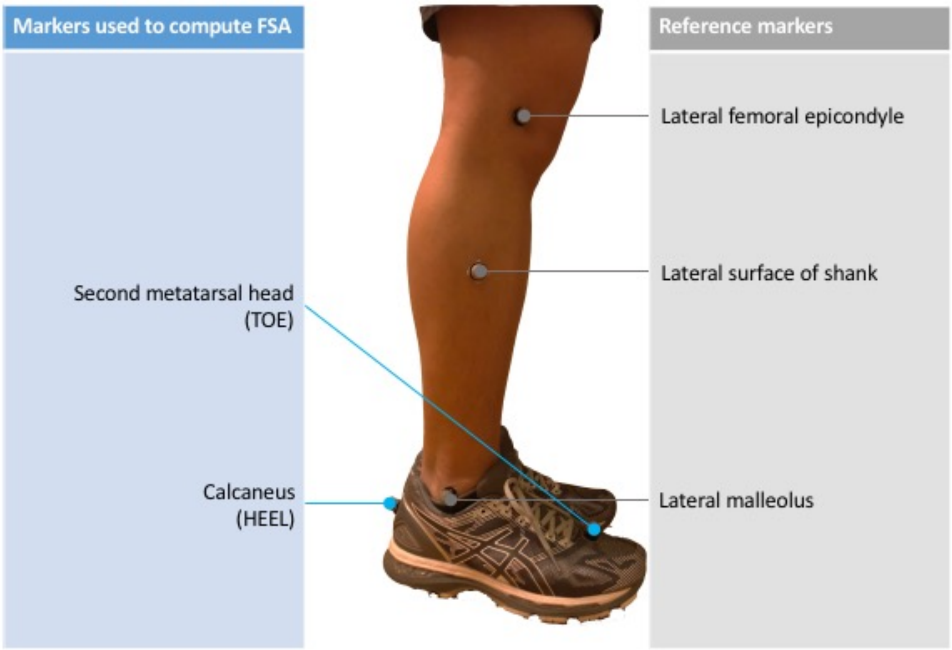

Figure 4.1 Position of reference markers, TOE and HEEL marker for processing footstrike angle
FSA, footstrike angle

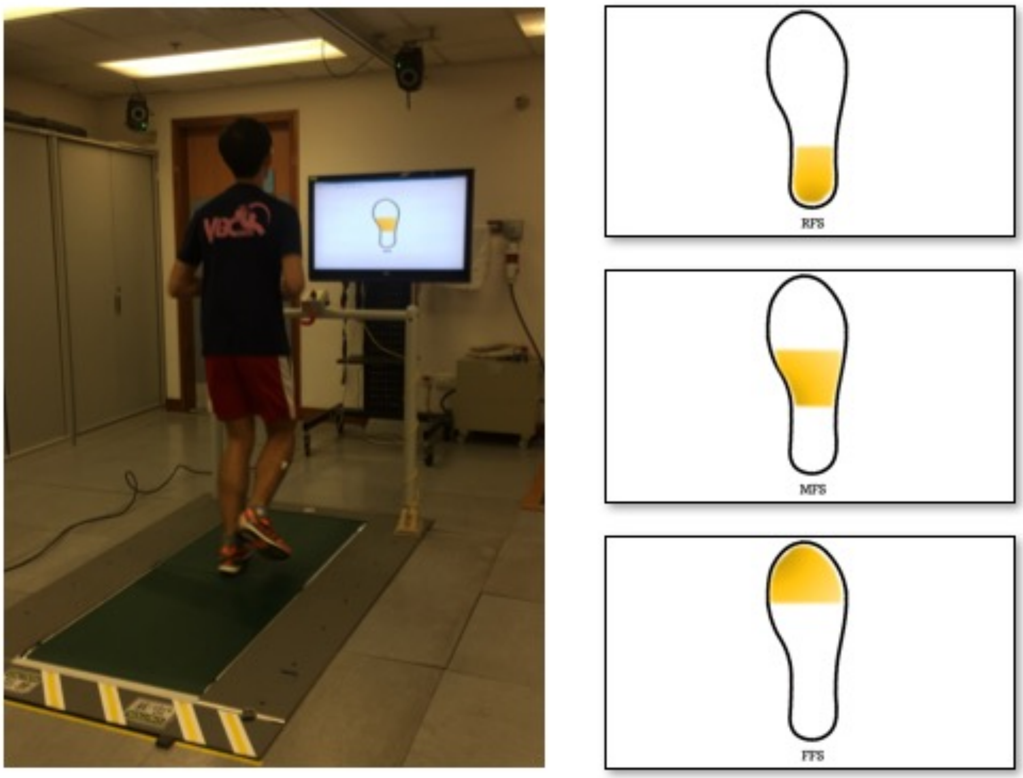

Figure 4.2 Visual footstrike information provided to participants for rear- (top), mid- (middle) and forefoot strike (bottom)
RFS, rearfoot strike; MFS, midfoot strike; FFS, forefoot strike

4.2.5 Data analysis

Based on the procedure described in previous studies to obtain impact loading from GRF collected from an instrumented treadmill (Cheung and Davis, 2011; Zhang et al., 2016), kinetics data were filtered by fourth-order Butterworth low-pass filter with a cut-off frequency of 50 Hz. A cut-off threshold of 10 N was used to identify IC and toe-off (Crowell et al., 2010). Loading rates, including VALR and VILR were obtained by the method previously used in other studies (Crowell et al., 2010; Davis et al., 2016), procedures have been described in section 2.3.

Marker trajectories were also filtered by a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz (Sinclair et al., 2013). The HEEL and TOE marker on the right limb was used to process the FSA. Ankle and knee joint angle and moments were computed based on the validated Plug-In Gait model detailed in section 2.2 (Kadaba et al., 1989; Winter, 2009), applying the anthropometry data, body mass and body height of each subject for subject-specific calculation. The linear fit of the slope in the sagittal moment-angle profile between IC and maximum ankle dorsiflexion and knee flexion were presented as ankle (Figure 4.3a) and knee joint stiffness (Figure 4.3b) respectively.

VALR, VILR and joint stiffness were normalized to participant's body weight. Variables of the right side were selected and averaged across all right footfalls during the one-minute data collection.

In each condition (Pre and Post), twenty right footfalls were randomly selected by MATLAB function *rand()* and the variables were processed for the difference before and after the training. The VALR, FSA, ankle and knee joint stiffness of the selected footfalls in the Pre-training condition were subtracted by those in Post-training condition, a positive value of change indicates reduction.

4.2.6 Statistical analysis

Paired *t*-tests were used to compare the dependent variables of Pre-training Post-training and Cohen's *d* was calculated to evaluate effect size. Separate Pearson's *r* was computed to assess the relationship between the change in VALR and the change in FSA or joint stiffness. The global level of significance for all statistical calculations was set at 0.05. Statistical tests were computed using SPSS for Windows, Version 22 (SPSS, Inc., Chicago, IL, USA).

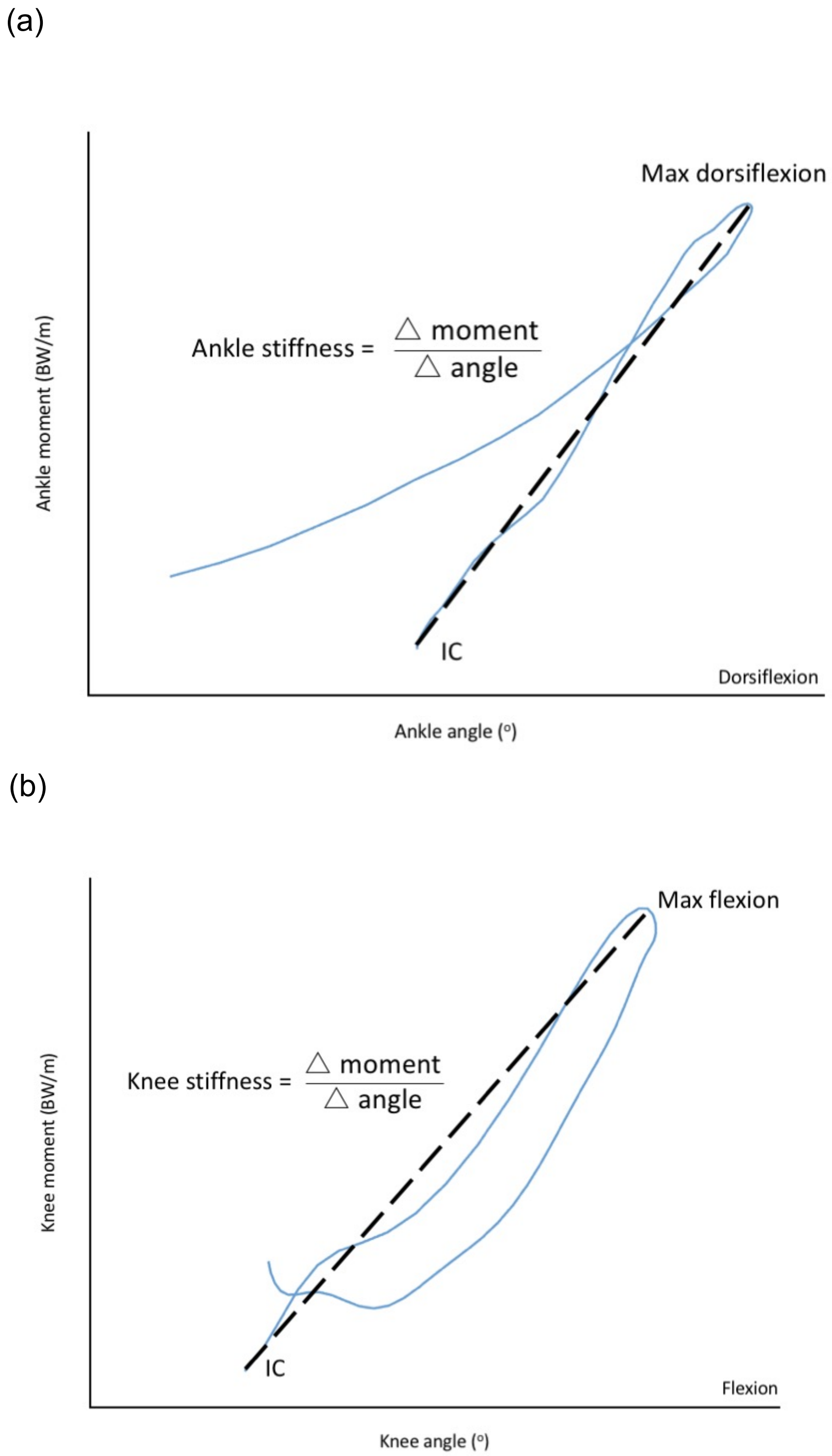

Figure 4.3 Moment-angle curve of the (a) ankle and (b) knee for one stance phase indicating the calculation of joint stiffness

IC, Initial contact; BW, Bodyweight

4.3 Results

The participants' usual training speed was 2.83±0.26 m/s. Results of the paired *t*-tests were presented in Table 4.2 and Figure 4.4. The Post-FSA (9.9±6.7^{o}) was significantly lower compared to the Pre-FSA (18.2±3.4^{o}) (p=0.001, Cohen's d=1.42). No difference was observed in the loading rates Pre- versus Post-training (p>0.134, Cohen's d=0.38-0.39). In addition, there was no significant difference in the ankle stiffness (p=0.960, Cohen's d=0.11), but the knee joint stiffness increased (p=0.005, Cohen's d=0.88) compared to Pre-training values.

The relationship between the change in VALR and the change in FSA, ankle and knee joint stiffness were assessed by Pearson's r. There was a positive moderate correlation between the change in VALR and ankle joint stiffness (p<0.001, r=0.664; Figure 4.5). Yet, only negligible correlation between the change in VALR and FSA (p<0.001, r=0.366), and no correlation between the change in VALR and knee joint stiffness (p=0.863, r=0.010).

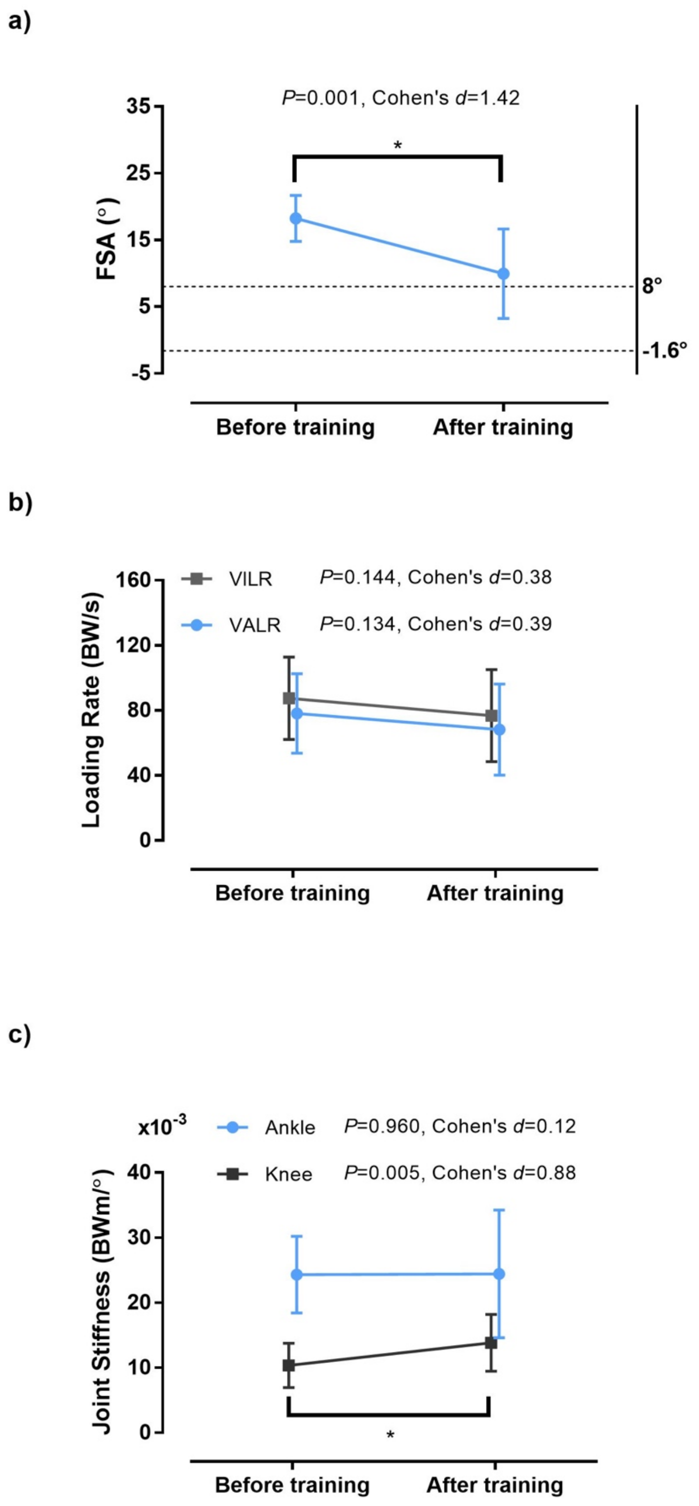

Figure 4.4 Footstrike angle (FSA), vertical average loading rate (VALR), vertical instantaneous loading rate (VILR), ankle and knee joint stiffness of the trained limb before and after training.

The dotted line in Figure 4.4a indicates the cut-off between footstrike patterns.

* indicates significant difference before and after training.

BW, body weight

Table 4.2 Biomechanical data (mean±SD) during Pre- and Post-training running

	Pre-training	**Post-training**
FSA (°)	18.2±3.4	9.9±6.7*
VALR (BW/s)	78.1±24.4	68.2±28.0
VILR (BW/s)	87.5±25.3	76.9±28.4
Ankle joint stiffness (10^{-3}, BWm/°)	24.3±5.9	24.4±9.8
Knee joint stiffness (10^{-3}, BWm/°)	10.3±3.4	13.8±4.4*

FSA, Footstrike angle; VALR, vertical average loading rate; VILR, vertical instantaneous loading rate, BW, Bodyweight

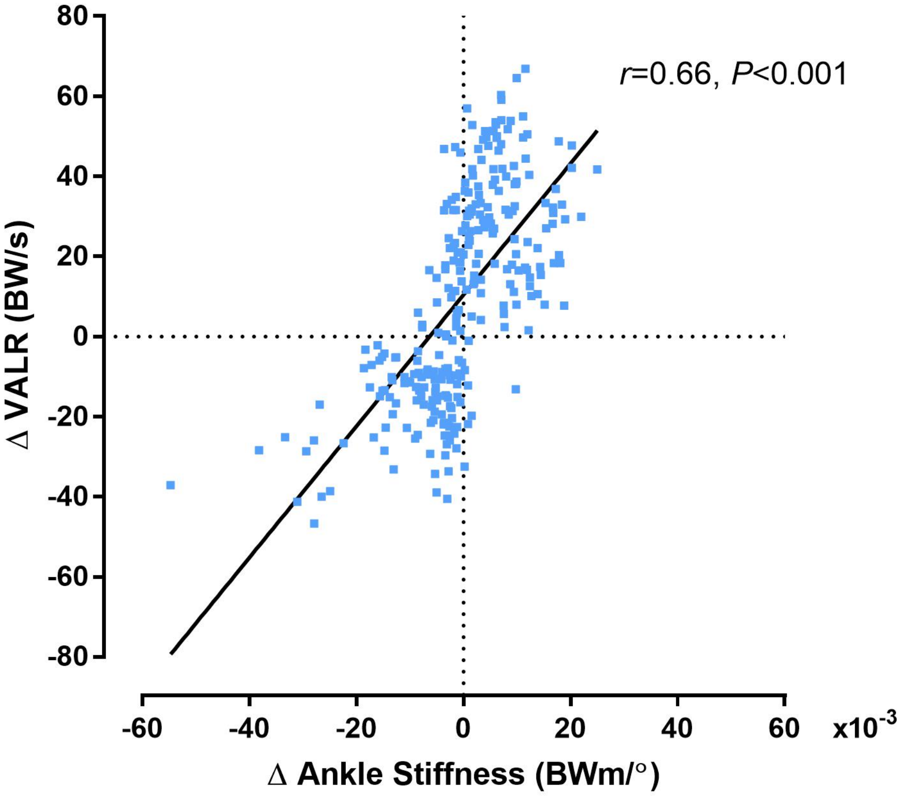

Figure 4.5 A moderate positive correlation between the change in ankle stiffness and the change in vertical average loading rate (VALR) before and after training.

BW, body weight

4.4 Discussion

This study sought to evaluate a gait retraining with footstrike information on its effect on footstrike pattern, impact loading and joint stiffness. We found a significantly reduced FSA after the training. Regarding impact loading, however, the results did not support our hypothesis of reduced impact loading upon completion of training. As for joint stiffness, knee stiffness was found to be higher after the training, suggesting a re-organization of the control strategy when runners attempt the modified running gait.

4.4.1 Footstrike pattern

The FSA was reduced by more than 8° from 18.2° to 9.9°, yet a FSA of greater than 8° is classified as a RFS (Altman and Davis, 2012). Our hypothesis on the footstrike pattern change remains debatable. On one hand, we observed a reduction in FSA, results supported a footstrike modification that trends towards a MFS after the training. However, a complete transition of RFS to MFS was not definite. It is important to note that there was a larger variance in FSA between participants after training, with a SD of 6.7°, the FSA was found spread around the threshold between MFS and RFS i.e. 8° (Figure 4.4a). We observed that some participants would run with an FSA slightly above 8° during the training when feedback was not provided, potentially indicating over-reliance on the feedback and in turn compromise the effect of the training. This variance in FSA recorded around the margin of 8° in the Post-training running trial suggested slightly inconsistent effect between individuals.

Another explanation for the difference between our findings and other studies with successful footstrike pattern modification upon training was the target of the gait retraining (Cheung and Davis, 2011; Roper et al., 2016). In the earlier study promoting footstrike pattern modification (Cheung and Davis, 2011), runners were instructed to eliminate buzzer noise by avoiding RFS landing, yet runners could achieve the target by both adapting a MFS or FFS pattern. Running with a NHS could be easier to achieve than to specifically achieve MFS. Participants in our study was instructed not to over-correct their footstrike into a FFS, with the MFS being in the intermediate zone, participants could become cautious and kept their FSA just below the threshold.

Furthermore, footstrike information, unlike peak impact force (Crowell and Davis, 2011) was discrete. This type of feedback was suggested to be simple and easier to understand (Sigrist et al., 2013), yet it could hinder the runners on analyzing the magnitude of their correction during the learning phase of the gait retraining or further improve when the target was already met. Findings of two similar gait retraining studies that used PPA measured at the tibia as feedback could demonstrate the effect using different types of feedback. The earlier study (Crowell and Davis, 2011) displayed the PPA-time graph visually, a line on the graph indicated the target PPA, while in the more recent study (Cheung et al., 2018) a colored signal (red or green) indicated the PPA value above or below the threshold. Both studies reported a reduction in VALR, but Crowell and Davis reported a larger effect size (Cohen's *d*=1.50) with continuous accelerometer data as compared to Cheung *et al.* (Cohen's *d*=0.97) using discrete signals. The difference in the effect sizes suggested possible difference between the present study and previous gait retraining studies.

4.4.2 Impact loading

Based on previous findings from gait retraining studies on impact loading (Altman and Davis, 2009; Chen et al., 2016; Giandolini et al., 2013), and the immediate reduction of loading rates upon switching to a MFS (Arendse et al., 2004; Chen et al., 2016; Giandolini et al., 2013). We hypothesized that the present gait retraining program would also be effective in lowering the VALR and VILR of RFS runners. Surprisingly, the results of the present study did not support this hypothesis. Our findings suggested that by providing footstrike information to runners during gait retraining might not be as effective on impact loading reduction as other types of feedback including PPA (Cheung et al., 2018; Crowell and Davis, 2011), step rate (Willy et al., 2016) and the GRF curve mentioned in Chapter 3 (Chan et al., 2017). No significance difference was found in VALR and VILR, moreover, some participants had increased VALR up to 26.1 BW/s after the training. Altman and Davis also reported similar findings, when their participants attempted to do a MFS after a short practice, they recorded an immediate increase in VALR and VILR in a subgroup (Altman and Davis, 2009).

4.4.3 Joint stiffness

Stiffness in individual joints on the lower extremity contributes to the overall vertical stiffness of the body within the stance phase during running (Kuitunen et al., 2002). Hamill *et al.* suggested that by changing the footstrike pattern, the ankle and knee joint stiffness would also change (Hamill et al., 2014). Our results showed increased knee joint stiffness in the Post-training condition, which was similar to when habitual RFS runners attempt to use FFS in previous studies (Hamill et al., 2014; Laughton et al., 2003). A stiffer knee was useful in maintaining the posture while using the modified gait pattern. However, unlike the mentioned studies, we did not observe a significant reduction in ankle stiffness. Such findings could in part explain the absence of difference in impact loading. It has been supported by previous studies that a stiffer joint would reduce shock attenuation and was found to be associated with harder landings (Baltich et al., 2015; Mauroy et al., 2014). Joint stiffness is based on the moment-angle relationship of a joint, and therefore related to the deformation of the joint and the change in the joint moment in the early stance phase. Landing with a MFS would theoretically allow the ankle a larger range for plantarflexion, favoring a more compliant ankle. Yet, muscle activation pattern associated with different footstrike pattern would also affect the attenuation of energy during impact (Ahn et al., 2014; Hamill et al., 2014). In our study, participants did not adopt the same re-organization strategy of lower-limb joints as with attempting to run with a FFS, indicating potential difference in neuromuscular control of movement exists between varies footstrike pattern.

We conducted correlation analysis to explicate the expected change in VALR Pre- and Post- gait retraining based on FSA and joint stiffness. We found a negligible correlation between the change in VALR and FSA, suggesting the magnitude of reduction in FSA is not the main determinant of the change in VALR. In Nordin *et al.*'s study, a subtle-RFS was defined as the intermediate between obvious-RFS and MFS, with FSA around the RFS/MFS boundary i.e. 8° (Nordin et al., 2017). The VILR of obvious-RFS, subtle-RFS, MFS and FFS did not follow a linear trend, corresponding to our finding; the reduction of FSA might not be proportional to the reduction in VALR. The change in ankle stiffness, however, was found to have a moderate positive correlation with the change in VALR. Participants that ran in the modified running gait with increased ankle stiffness were found to have increased VALR. The strategic modulation in ankle and knee joint stiffness during the modified gait pattern could have an important role on the effects of the gait retraining on impact loading. Knee joint stiffness was found to be higher after the gait retraining, yet no significant correlation was found with VALR. With a stiffer knee after training, the ankle stiffness was therefore crucial in determining the change in VALR.

4.5 Conclusion

In conclusion, visual-feedback gait retraining to promote MFS was found effective in reducing runners FSA but not necessarily lead to a switch in footstrike pattern. Surprisingly, the changes in impact loading were inconsistent among trained runners. The modulation of ankle stiffness could be a determinant for the impact loading when runners attempt to change their footstrike pattern.

CHAPTER 5

INTER-LIMB SKILL TRANSFER AND SUSTAINABILITY OF GAIT RETRAINING TO PROMOTE MIDFOOT LANDING PATTERN

5.1 Introduction

The practical implications of gait retraining has been supported by scientific evidence; faulty running mechanics that were linked to RRIs could be corrected through systematic gait retraining programs (Crowell and Davis, 2011; Noehren et al., 2011). Vertical loading rate, which was found to be strongly associated with a series of RRIs, was often the target for treating injured or at-risk runners (Cheung and Davis, 2011; Crowell and Davis, 2011; Willy et al., 2016). Furthermore, as discussed in Chapter 3, gait retraining could prevent RRIs in healthy runners as well. The injury occurrence within one year after gait retraining was 62% lower among trained runners as compared to the controls based on the large-scale RCT (Chan et al., 2017). These findings has made gait retraining a popular tool for treating and reducing the risk of an RRI (Davis and Futrell, 2016).

In many gait retraining studies, real-time biofeedback was provided to runners during the training. The PPA, a surrogate measure of loading rate (Blackmore et al., 2016; Zhang et al., 2016), was widely used as feedback for gait retraining (Clansey et al., 2014; Crowell and Davis, 2011; Wood and Kipp, 2014). The setup required a light-weight accelerometer taped onto the surface of the runner's shank, data collected could be displayed raw (Crowell and Davis, 2011) or processed to be shown as traffic-light signals (Clansey et al., 2014) in order to help runners reduce impact. In all three studies, the accelerometer was placed on a single side of the two lower limbs, the feedback shown to the runner was based on the selected limb only.

In Crowell and Davis's study, they selected the limb with higher impact loading recorded during the screening as the training limb, while neither Clansey *et al.* nor Wood and Kelp provided justification for the limb selection.

Healthy adults displayed symmetrical motor learning in walking (Krishnan et al., 2017), therefore it is still plausible that a single-limb feedback setup is as effective as one that provides feedback for both sides. In the study presented in Chapter 3, the GRF shown involved both left and right footfalls, runners were able to see the force information of both limbs and correct both sides at the same time. The effect size of that study for loading rate reduction was between 0.99 to 1.12 for the training group. In another study the used the same training schedule, single-limb PPA graph was provided as feedback, the effect size for loading rate reduction was between 1.5 to 1.7 (Crowell and Davis, 2011). This could suggest that single-limb training could be as effective as one that involved both sides.

That being said, the effects of a gait retraining should not be evaluated only from one side. It is important to note that any gait retraining studies, the evaluation was based on the training limb only (Cheung et al., 2018; Cheung and Davis, 2011; Clansey et al., 2014; Crowell and Davis, 2011; Wood and Kipp, 2014). The reported effect of these studies could be overstating, as the effect would be greatly compromised if the modified gait fails to be transferred to the untrained limb. A comprehensive evaluation of a gait retraining should involve the assessment of inter-limb skill transfer. Inter-limb skill transfer was defined as a phenomenon where the learning of a motor skill in one limb could be transferred to the opposite limb (Krishnan et al., 2017). The findings in inter-limb skill transfer were inconsistent among different studies. Some studies has shown motor learning to be asymmetric, where one side benefited after a short-term motor training task but the opposite side did not (Morris et al., 2009; Stöckel and Wang, 2011). Choi *et al.* have suggested that the right and left leg need to be trained individually (Choi and Bastian, 2007). This research group used a split-belt treadmill to train young adults into walking at different directions and different speeds in opposite legs, their results supported that motor adaptation to the new gait could be learnt independently. On the other hand, Krishnan *et al.* found significant transfer of motor skills from the trained side to the untrained side after a gait retraining to increased hip and knee flexion during the swing phase (Krishnan et al., 2017). Such controversies have made it necessary for gait retraining studies to evaluate the effect for both the trained and untrained limb, in the case of single-side feedback.

Apart from the inter-limb skill transfer, the sustainability was also considered a big concern in the practical aspect of gait retraining. Regarding previous gait retraining studies which promotes a footstrike pattern switch, follow-up assessments have been conducted (Cheung and Davis, 2011; Davis and Futrell, 2016; Roper et al., 2016). Roper *et al.* conducted a biomechanical assessment one month after the last session, while for the case studies, the follow-up assessments were conducted either three months or twelve months upon completion of the training. Since the gait retraining was designed to correct gait pattern at risk and subsequently reduce the rate of injury or relieve pain, it is important for the training effect to last; therefore it is important to conduct either a short-term or long-term follow-up on trained runners. Clansey *et al.* noticed a rebound toward Pre-training loading rate values in runners one month after the training, even though the effect size between Pre- and Post-training was large (Cohen's *d*=0.75-0.77) (Clansey et al., 2014). The immediate effect of a gait retraining to promote footstrike pattern transition has been discussed in Chapter 4, yet the sustainability of the modifications remains unknown. Hence, it would be clinically meaningful to assess the short-term effect and further optimize the protocol if necessary.

The purpose of this extension study was to provide a more comprehensive evaluation of the gait retraining protocol, by assessing the inter-limb skill transfer and short-term sustainability of the effects on footstrike pattern and impact loading. It was hypothesized the footstrike pattern and impact loading after the training would be similar in both the trained and untrained limb, and in addition, the effect would persist at the one-month follow-up.

5.2 Methods

5.2.1 Participants

As an extension to the study presented in Chapter 4, all participants included in the gait retraining study were also expected to be included in this study. All participants were informed of the follow-up assessment prior to signing of the consent. On top of the inclusion and exclusion criteria described in section 4.2.1, runners who ran less than 15 km per week between the time of the Post-training assessment and the Follow-up assessment were excluded from further analysis.

Three out of the fourteen runners were excluded from this extension study. Two were unable to return to the lab within the time frame (30±5 days) for the Follow-up assessment due to personal reasons, while another runner only logged a 5-km run before the scheduled re-assessment.

The mean and SD of the characteristics of the included participants are presented in Table 5.1.

Table 5.1 Characteristics of participants

Characteristics	**Mean and SD**
Age (year)	38.8±6.1
Weight (kg)	72.4±5.9
Height (m)	1.77±0.04
Weekly mileage (km)	31.1±13.4
Running experience (year)	5.5±3.7
Testing and training speed (ms^{-1})	2.82±0.27

5.2.2 Data collection

Data collection for the Pre- and Post- training condition was detailed in section 4.2.3. The right side was selected as the training side. All participants completed the 8-session gait retraining with real-time footstrike information of the right foot being displayed visually in front of them. Upon completion of the gait retraining detailed in section 4.2.4, runners returned to their usual training schedule. Feedback on footstrike pattern was not available to runners, but they were encouraged to maintain the newly learnt gait pattern in their natural running environment. An additional Follow-up assessment was conducted on the instrumented treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) in the Gait and Motion Analysis Laboratory of the Hong Kong Polytechnic University within 30±5 days from the last session of training.

Each participant wore his/ her own pair of shoes that were used during the training. HEEL and TOE markers from the validated model described in section 2.1 were firmly affixed, there were a total of four reflective markers on both sides (Altman and Davis, 2012). The treadmill speed was adjusted to match the training and testing speed of previous assessments. After five minutes of warm-up, kinetics and kinematics data were sampled at 1,000 and 200 Hz respectively for one minute.

5.2.3 Data analysis

Marker trajectories and kinetics data were filtered and processed in the same manner as mentioned in section 4.2.5. FSA was processed for both the trained and the untrained side based on the method mentioned in section 2.1.

The GRF was synchronized with the marker trajectories, for each GRF segment (IC to toe-off), the corresponding marker positions of the right HEEL and right TOE markers were used to determine the side of limb. The GRF segment was considered to be corresponding to a right footfall, if the vertical marker position of the right HEEL and/or right TOE was less than 0.1 m at IC. Otherwise, the GRF segment would be assigned as a left foot stance. This threshold was selected based on the minimum vertical positions of the HEEL and TOE markers within the running trial, and the value reported in a study which considered the variance between footstrike pattern (Handsaker et al., 2016). The VALR and VILR of each side was calculated by the method described in section 2.3 separately. All loading rates were normalized to participants' body mass, and all variables were averaged across all footfalls of the same side within the one-minute data collection.

5.2.4 Statistical analysis

A 2 x 3 repeated measures ANOVA (Side x Time) were used to compare the impact loading variables and FSA between footfalls of the trained (right) and untrained (left) side against time-points (Pre, Post and Follow-up). Post-hoc analysis was conducted for the main effect of Time on all the variables. The Mauchly's test of sphericity was used to test the assumption of sphericity, a Greenhouse-Geisser correction was applied in the case of the violated assumption. The global level of significance for all statistical calculations was set at 0.05. Statistical tests were computed using SPSS for Windows, Version 22 (SPSS, Inc., Chicago, IL, USA).

5.3 Results

The FSA of both legs were listed in Table 5.2 and Figure 5.1. There was no significant interaction between Side and Time (F(1.33,13.30)=0.66, *p*=0.472). However, there was a main effect of Time on FSA (F(1.21,13.06)=13.84, *p*=0.002), post hoc analyses found significant difference between Pre and Post (*p*=0.006, Cohen's *d*=1.46), and also Pre and Follow-up (*p*=0.016, Cohen's *d*=1.24).

Regarding loading rates, the 2 x 3 repeated measured ANOVA showed no significant interaction between side and time for VALR (F(2,20)=0.30, *p*=0.741) and VILR (F(2,20)=0.38, *p*=0.689). No significant difference in impact loading was observed between different time-points.

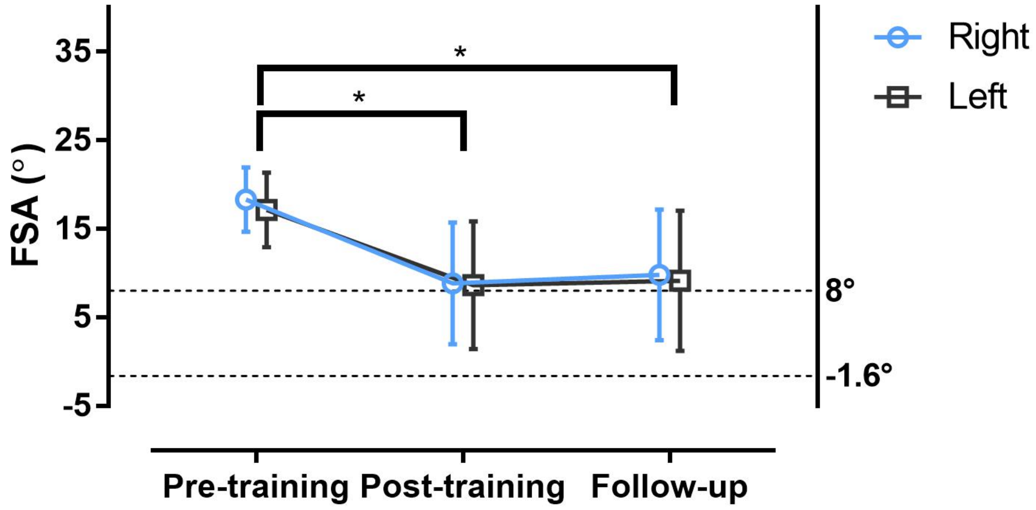

Figure 5.1 Footstrike angle (FSA) of the right and left foot in three time-points.

The dotted line indicates the cut-off between footstrike patterns.

* indicates $p<0.05$ in pairwise comparisons between time-points

Table 5.2. Biomechanical data (mean, SD and *p*-values) of the trained and untrained limb in three time-points

	Trained side (Right)			Untrained side (Left)				
	Pre-training	Post-training	1 month Follow-up	Pre-training	Post-training	1 month Follow-up	Side x Time *P*-value #	Time *P*-value +
FSA (°)	18.3±3.6	8.9±6.9	9.8±7.4	17.1±4.2	8.6±7.2	9.2±7.9	0.472	0.002*
VALR (BW/s)	77.29±25.30	64.26±30.24	65.49±30.87	76.15±31.38	65.14±32.65	64.39±36.54	0.741	0.107
VILR (BW/s)	86.70±26.75	72.97±30.80	73.62±32.84	85.08±32.84	73.95±33.72	72.82±37.66	0.689	0.107

FSA, footstrike angle; BW, body weight; VALR, vertical average loading rate; VILR, vertical instantaneous loading rate

P-value from 2 x 3 repeated measures ANOVA (Side x Time-points)

+ *P*-value for main effect of time

* *P*<0.05

5.4 Discussion

This study sought to provide a more comprehensive evaluation for a gait retraining that promoted MFS landing by comparing the FSA and loading rates between the trained and the untrained limb. FSA and loading rates were comparable between sides. Additionally, this study also compared the FSA and loading rates between various time-points, including before, after and one month after the gait training. We found that the reduction in FSA could be maintained across time.

5.4.1 Inter-limb skill transfer

In this study, the real-time feedback information was provided for the right limb, such design made the assumption that humans run symmetrically, and the gait modification could be transferred to the untrained side. Single-limb feedback has been used for a large number of gait retraining studies (Cheung et al., 2018; Cheung and Davis, 2011; Clansey et al., 2014; Crowell and Davis, 2011; Noehren et al., 2011), but interestingly, none of these studies has evaluated the effect of the gait retraining based on the running mechanics of both sides. Results based only on the trained limb might overstate the significance of the training protocol in a practical setting, if the modification was only demonstrated in one side. Moreover, some studies have reported that injured runners would modify their running mechanics by compensation of the uninjured side in the presence of pain (Noehren et al., 2012b; Tashman et al., 2004b), it is therefore possible that during gait retraining, runners would compensate the untrained side to reach the training target .

According to the results of the 2 x 3 repeated measures ANOVA, no significant interaction was found i.e., the effect of Time was not different between the trained (right) and the untrained (left) side. We found no side-specific difference. This indicated that the effect of training could potentially be transferred to the untrained limb, even though runners only received feedback of the right foot throughout the whole training. Even though both Post-FSA for the right and left side were larger than 8° and still regarded as RFS, a significant reduction in the FSA has been observed. This result suggested that a single-limb training was adequate to reduce the FSA of both sides, and future gait retraining could adopt such a design as well. In fact, it is more economical for single-side training, the technological demand and the cost of sensors to provide feedback to runners could be reduced, potentially enhancing the practicability and cost. Besides, runner could be overwhelmed with feedback if both sides were provided. In a study that compared the reaction time of runners in shoes and barefoot by using a simple button-pressing task, the average reaction time to a visual stimulus while running was found to be 0.28±0.03 s (Snow et al., 2018). Another test that focused on lower-body response to visual stimulus reported a even longer reaction time, an average of 0.529±0.112 s between male and female participants (Spiteri et al., 2013). In the present study, depending on the stride frequency, the feedback was refreshed every 0.67 – 0.92 s, this allowed sufficient time for runners to make adjustments based on the feedback. However, the response and motor adjustment time would be halved if feedback was provided for both sides, increasing the chance of cognitive overload (Sigrist et al., 2013).

Although we did not collect kinematics data during training sessions, our participants have pointed out that they were focused on correcting the right foot during the first few sessions. Upon being confident in executing a MFS with their right foot, they would attempt to change the footstrike pattern of the left foot as well. It is plausible that the training of the right foot has allowed runners to develop a link between the somatosensory feedback from the plantar surface of the foot and the footstrike information provided. An error detection and correction mechanism could potentially be transferred and applied on the alternative limb.

This study has demonstrated inter-limb transfer within participants, yet the mechanism behind has not been investigated. Therefore, it is important to note that the inter-limb skill transfer was only observed in the FSA only. The lack of significant changes in the loading rates made it impossible to detect the transfer of effect on impact loading. Footstrike pattern, as compared to other biomechanical parameters related to RRIs is more explicit. Runners could attempt or practice modifications on the left side outside of the training sessions, possibly learning to adopt a MFS based on self-correction. Further investigation on the inter-limb skill transfer would be required to test the effect on reduction of impact loading.

5.4.2 Sustainability

In this study, we have included a follow-up assessment to examine the short-term retention of the hypothesized training effect. The results on FSA were in line with our hypothesis, post hoc analysis revealed a significant reduction in FSA from baseline even after one month. The sustainability of the training effect reflected the internalization of the newly learnt gait pattern, runners could naturally execute the modified pattern without having to rely on feedback (Barrios et al., 2010). Our results showed that an eight-session training was sufficient in development of a natural running gait that could be sustained for at least one month. This finding has notable practical significance, gait retraining was often designed to correct gait pattern at risk and subsequently reduce the rate of injury or relieve pain, it is important for the training effect to last.

The sustainability of impact reduction, however, could not be examined in this study due to the absence of changes in loading rate between the Pre-training condition and Post-training condition.

5.5 Conclusion

In conclusion, trained runners who underwent a single-limb feedback gait retraining which promotes MFS were able to lower the FSA in both the trained side and the untrained side. Such reduction was shown to be sustained and the FSA was maintained during the 1-month follow-up. However, we did not observe any significant difference in loading rates before and after the training. Therefore, this study was unable to determine whether the effect on impact loading could be transferred to the opposite limb and sustained.

CHAPTER 6

EVALUATION OF FOOTWEAR ON FOOTSTRIKE PATTERN AND IMPACT LOADING

6.1 Introduction to the features of running footwear

Recreational running has become one of the top five popular form of exercise across the world (Hulteen et al., 2017), and it is well reflected by numerous races and running events organized each year. Locally, the renowned Standard Chartered Hong Kong Marathon accommodated a record-breaking 74,402 participants in 2017 (*2018 Standard Chartered Hong Kong Marathon - Marathon Race Handbook*, 2018). Compared to the same event held ten years ago, the number has almost doubled. This trend was not limited to local events; the number of runners in the Boston Marathon held in 2017 was also threefold of that held in 2007 ("Population and growth of the Field," 2018). The arising running population leads to a high demand in running apparels, which can be seen from the boost in running footwear market (Hennig, 2011). Over the past forty years, various of shoes have been developed for particular aims, such as for daily training or for competition (Hennig, 2011; Rixe et al., 2012). However, most of the manufactures would take injury prevention and comfort as two important features of their shoe design (Reinschmidt and Nigg, 2000).

From a biomechanical point of view, the rate of RRIs was considered relate with higher impact loading, and such association has been demonstrated by several past studies (Davis et al., 2016; Milner et al., 2006; Pohl et al., 2009), so as our previous work (Chapter 3). Landing with a MFS or FFS was also reported to reduce the impact loading (Arendse et al., 2004; Chen et al., 2016; Lieberman et al., 2010), and thus reduce RRIs risk. Therefore, reducing the impact loading experienced by runners at touchdown and promoting a softer landing have been the targets of footwear design. A variety of cushioning technologies, materials and thickness of the midsole have been introduced, aiming to better attenuate the shock and protect the runner against RRIs (Dinato et al., 2015; Hennig, 2011).

Apart from shock attenuation, the cushioning in the running footwear has also been suggested to enhance comfort. Providing a comfortable running experience to the runner was also considered an important aspect of footwear design (Reinschmidt and Nigg, 2000). A comfortable pair of shoes was considered effective in preventing injury and fatigue, also to enhance performance (Meyer et al., 2018; Miller et al., 2000). A study on shoe inserts found the most comfortable condition was able to reduce injury frequency (Mündermann et al., 2001). Varies midsole stiffness and cushioning technologies have been tested, yet there has been no consensus as to what constitutes maximum subjective comfort (Dinato et al., 2015).

In this chapter, two studies related to footwear design and running biomechanics are presented. The first study focused on the effect of extreme midsole cushioning on subjective comfort, impact loading and footstrike pattern. The second study described how the context of footwear would affect the perception of comfort, and the effect on runners' biomechanics.

6.2 Midsole cushioning

6.2.1 Maximalists

By modifying the mechanical cushioning system within the midsole, footwear companies aims to reduce the shock experienced by runners (Rixe et al., 2012). However, the effectiveness is still debatable. Theoretically, the midsole deforms during foot contact, which lengthens the energy storage and return process. As demonstrated in a previous study (Clarke et al., 1983), such spring-like effect played by the midsole delayed the VIP and furthermore reduced the loading rate in runners. In a study which compared six different shoe models, the highest VILR was recorded when runners ran with the shoes with least cushioning (Dixon, 2008). However, recent research showed inconsistent findings regarding the effectiveness of cushioning. A previous study showed gender divergence regarding the effectiveness of cushioning (Logan et al., 2010). Specifically, male runners reduced their loading rates with cushioned shoes, but such results were not observed in female runners. More recently, Baltich *et al.* conducted a study using footwear with different midsole hardnesses, they found the highest VIP with the softest midsole, potentially leading to higher loading rates (Baltich et al., 2015). Such discrepancies in previous studies could possibly be explained by the difference in the design of each shoe model, and therefore, new studies are still warranted to understand the effect on impact attenuation based on a specific design.

A relatively new type of footwear, known as the MAX, features an extra thick layer of EVA midsole, and a relatively low heel-to-toe drop. Addressed by the manufacturer, its novel midsole technology aims to enhance comfort and attenuate impact (“The HOKA® Difference | Technology by HOKA ONE

ONE®," 2018). Meanwhile, a flat midsole design could potentially promote MFS landing pattern (Horvais and Samozino, 2013). In addition, the "meta-rocker" design, featured as a curved outsole, was suggested to reduce stride length in running (Hazell and Chockalingam, 2009). With the interaction effects of the midsole thickness, low heel-to-toe drop, and the curved outsole, MAX could potentially change a runner's gait pattern and impact loading.

The other end of the cushioning spectrum would be the minimalist shoes (MIN). It is usually characterized by a low stack height and minimal amount of cushioning (Esculier et al., 2015). Thus, several studies have compared biomechanical parameters between MAX and MIN, as well as MAX and conventional shoes (CON). In Sinclair *et al.*'s study, VILR experienced by runners when running in MAX was less than half of that in MIN. Interestingly, MAX did not induce a lower loading rates comparing running with CON (Sinclair et al., 2016). Similar results were reported by another study testing a different model of MAX, the VILR was significantly increased by 17.2±5.1 BW/s when habitual CON runners switch into MIN, but not when they switched to MAX (Agresta et al., 2018). Surprisingly, the running trials in both studies were conducted on a level surface. Given that MAX was designed for trail runners, and this group of runners would encounter slopes during practice and competitions, It is possible that MAX would perform differently when compared to CON during downhill running, in which the impact loading has been reported to be higher than level ground running (An et al., 2015; Gottschall and Kram, 2005). *At this time, we have limited understanding on the effect of MAX on impact reduction and the footstrike pattern, especially in a downhill surface.*

Besides the effect on running biomechanics, the claimed effect on comfort by the MAX has not been assessed. Comfort and fit were found to be strongly correlated (r=0.90) to the overall liking of the footwear (Hennig, 2011), and runners were previously shown to favor softer materials in their footwear (Mündermann et al., 2001). With hardness being a dominating factor for comfort (Mündermann et al., 2001), MAX would likely be perceived as more comfortable than CON. *Currently, no published study has reported the perceived comfort in MAX while running on a level or downhill surface, thus by conducting such investigation, we could extend our knowledge on MAX.*

Hence, the aim of this study was to compare footstrike pattern and impact loading in runners with MAX and CON during level and downhill running. The secondary aim was to compare the subjective comfort of MAX and CON in the two surface conditions. It was hypothesized that the additional cushioning provided by MAX would promote NHS landing among runners and loading rates would be reduced in both surface conditions. Additionally, we hypothesized that the comfort rating would be higher in MAX in both running conditions.

6.2.2 Methods

6.2.2.1 Participants

A pilot study was conducted; the preliminary data was used for the sample size estimation. Based on the primary variable of interest, the vertical loading rates, an *a priori* power analysis was conducted using G*POWER 3.1 (Universität Kiel, Germany) to determine the sample size needed. The significance level was set as 0.05 and based on a power of 0.80, a total of 27 runners would be sufficient to power this study.

Recreational runners were recruited from local running clubs, inclusion criteria set for this study included: 1) within the age of 20-50, 2) regular shod runner with more than 8 km per week, 3) more than 1 year of running experience and 4) shoe size within the range specified in section 6.2.2.2. Runners were excluded if they sustained a RRI in the last six months or had previous running experience in the test shoe models (detailed in section 6.2.2.2). The experimental procedures were reviewed and approved by the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University. Informed consent was obtained from all participants prior to testing.

There was a total of twenty-seven participants in this study, all of them were included in the biomechanical analyses. Two participants were excluded from the comfort analysis due to data loss. The mean and SD of the characteristics of the twenty-seven participants and sub-group included for comfort analysis were presented in Table 6.1.

6.2.2.2 Footwear

Two types of running footwear were compared in this study: CON as the control condition, and MAX as interventional footwear condition (Figure 6.1). Specifications of the two models are presented in Table 6.2. Gender-specific sizing (US size 8-11 for male, US size 6-8 for female) was available for both models, participant's shoe size was measured with a Brannock device (Liverpool, NY, USA).

Table 6.1 Characteristics of participants included in biomechanical (N=27) and comfort analysis (n=25)

Characteristics	**Mean and SD (N=27)**	**Mean and SD (n=25)**
Gender	15 males, 12 females	14 males, 11 females
Age (year)	33.7±7.5	33.9±7.6
Weight (kg)	61.3±10.9	61.9±11.0
Height (m)	1.67±0.09	1.68±0.09
Weekly mileage (km)	33.1±14.7	32.4±13.6
Running experience (year)	5.0±3.2	4.9±3.1
Running speed (ms^{-1})	2.3±0.3	2.3±0.2

SD, Standard deviation

Table 6.2 Specifications of the testing shoe models

	CON	**MAX**
Brand	Adidas, Herzogenaurach, Germany	Hoka One One, Golera, CA, USA
Shoe model	Adizero boost	Clifton 3
Weight (g)	230	244
Stack height (mm)	24.4	34.5
Heel height (mm)	15.2	29.5
Heel-to-toe drop (mm)	9.2	5.0

CON, Conventional running shoe; MAX, Maximalist

Specification of both models based on men size US 9

Figure 6.1 Testing shoe models.
CON: Conventional running shoe (left), MAX: Maximalist with extreme cushioning (right)

6.2.2.3 Data collection

Each participant completed four running trials in the two footwear conditions: CON and MAX, on a level surface and a downhill surface with 10% declination. The test sequence was randomized using an online program (https://www.random.org). Two retro-reflective markers (HEEL and TOE) were firmly affixed onto the right calcaneus and second metatarsal head over the shoe of the participant before each running trial, according to the established model proposed by Altman and Davis detailed in section 2.1 (Altman and Davis, 2012). The three-dimensional positions of both markers were collected while the participant was standing on the running surface using an 8-camera motion capture system (MX, VICON, Oxford, UK).

In the beginning of each trial, participants were given four minutes to adapt to the running shoes on the instrumented treadmill (Force-sending tandem treadmill, AMTI, Watertown, USA) (Divert et al., 2005). GRF and marker trajectories were synchronized and recorded for one minute, sampled at 1,000 Hz and 200 Hz respectively. Immediately after each running trial, participants were instructed to rate the overall comfort level of the test shoes based on the five-minute run on the treadmill. An electronic version of the validated VAS to assess comfort was displayed on a monitor, with the left-most end of the 150 mm scale labelled “not comfortable at all” and the right-most end “most comfortable condition imaginable” (Mündermann et al., 2002). Participants used a computer mouse to point and click on the scale, the value was recorded in a customized MATLAB program (The MathWorks, Inc, Natick, MA, USA). In order to avoid fatigue, each running trial was separated by a fifteen-minute rest period (An et al., 2015; Bishop et al., 2006).

6.2.2.4 Data analysis

The time of IC was defined as the time the GRF exceeded 10 N (Crowell et al., 2010). The HEEL and TOE marker trajectories were filtered by a low-pass, fourth order Butterworth filter with 10 Hz cut-off (Sinclair et al., 2013). The FSA was computed using the filtered marker trajectories based on the procedure described in section 2.1. The FSA was corrected by subtracting the angle between a line joining the HEEL and TOE markers and the running surface while the subject was standing. Each participant was categorized into a HS ($FSA>8^o$) or NHS ($FSA<8^o$) runner based on the average FSA during the Control condition in each running trial (Altman and Davis, 2012; An et al., 2015).

Loading rates, including VALR and VILR, and FSA were calculated from the right side. Using a customized MATLAB program, the vertical GRF was filtered by a low-pass, fourth order Butterworth filter with a 50 Hz cut-off. The procedure for processing GRF data was based on previous studies (Cheung and Davis, 2011; Zhang et al., 2016a) and described in section 2.3. Both VALR and VILR were normalized to participant's body weight and average across all right footfalls.

The overall comfort was converted and presented as a percentage between 0 and 100 based on the location the participant clicked on the scale, where 100% indicates best comfort level.

6.2.2.5 Statistical analysis

All continuous variables were tested against a normal distribution using separate Shapiro-Wilk tests. McNemar's tests were used to compare the proportion of runners adopting a HS and a NHS pattern between the footwear conditions on each inclination condition.

Loading rates and the comfort scores were compared by a 2 x 2 repeated measures ANOVA (Footwear x Inclination). In addition, separate paired *t*-tests were used to compare VALR and VILR between MAX and Control under each inclination condition to assess the effect of footwear alone.

The global level of significance for all statistical calculations was set at 0.05. Statistical tests were computed using SPSS for Windows, Version 20 (SPSS, Inc., Chicago, IL, USA). Cohen's *f* and Cohen's *d* were calculated as effect size using G*POWER 3.1.

6.2.3 Results

Among twenty-seven participants, thirteen and seven participants were identified as NHS runners during level ground and downhill running respectively, the remaining participants were identified as HS runners. Only a few of the participants has switched their footstrike pattern while wearing MAX during level (7%) and downhill (15%) running. The number of participants adopting different footstrike pattern wearing MAX and Control during the two surface conditions and results of the McNemar's test are presented in Table 6.3.

Separate Shapiro-Wilk tests were conducted on the continuous variables, results indicated that VALR, VILR and comfort rating in all running conditions met the assumption of normality (p>0.050).

2 x 2 repeated measures ANOVA were conducted to examine the interaction of surface inclination and footwear condition in VALR, VILR and subjective comfort score. Significant interactions between the two factors were found in VALR (F(1,26)=4.31, p=0.048, Cohen's f=0.41) and subjective comfort (F(1,24)=4.58, p=0.043, Cohen's f=0.44), but not in VILR (F(1,26)=3.83, p=0.061, Cohen's f=0.38). Separate paired t-tests were performed on each surface condition to assess the sole effect of footwear. No significant difference was found between Control and MAX in both loading rates and comfort score (p>0.328, Cohen's d<0.256). However, we observed a greater comfort rating (p=0.001, Cohen's d=0.784) and higher VILR (p=0.045, Cohen's d=0.440) in participants running with MAX during downhill running.

Table 6.3 Number of participants adopting different footstrike pattern under conventional footwear (CON) and maximalist (MAX) during level ground and downhill running

Level ground

	MAX			
CON	HS	NHS	Total	McNemar's test *P*-value
HS	13	1	14	
NHS	1	12	13	
Total	14	13	27	>0.99

Downhill

	MAX			
CON	HS	NHS	Total	McNemar's test *P*-value
HS	18	2	20	
NHS	2	5	7	
Total	20	7	27	>0.99

HS, Heelstrike; NHS, Non-heelstrike

Table 6.4 Biomechanical data and comfort score (mean ± SD) between conventional footwear (CON) and maximalist (MAX) during level ground and downhill running

Level ground				
	CON	**MAX**	***P*-value**	**Cohen's *d***
VALR (BW/s)	59.2±15.6	58.5±13.8	0.763	0.07
VILR (BW/s)	73.7±16.7	75.5±17.0	0.589	0.11
Comfort (%)	68.4±17.0	72.3±12.0	0.328	0.26
Downhill				
	CON	**MAX**	***P*-value**	**Cohen's *d***
VALR (BW/s)	76.7±22.6	85.5±21.6	0.110	0.39
VILR (BW/s)	94.5±24.5	105.4±24.8	0.045*	0.44
Comfort (%)	62.0±17.0	75.7±17.9	0.001*	0.78

VALR, Vertical average loading rate; VILR, Vertical instantaneous loading rate; BW, Body weight
All comfort values were presented as a percentage, where 100% indicates best comfort level
* $p < 0.05$

6.2.4 Discussion

This study aimed to compare footstrike pattern and impact loading in runners with MAX and CON during level and downhill running. The running biomechanics on level ground was similar between the two test footwear conditions, but we found significantly greater VILR during downhill running in MAX. Regarding subjective comfort, participants rated MAX significantly more comfortable than CON during downhill running, but not level ground running.

Based on the previous findings on the difference in heel-to-top drop and changes to the footstrike pattern (Chambon et al., 2015; Horvais and Samozino, 2013), we hypothesized a transition from HS landing to NHS landing when running in MAX. However, majority of the participants maintained their original footstrike pattern when running in MAX. Owning to the well-established variance in running biomechanics between runners of different footstrike pattern (Cavanagh and Lafortune, 1980; Shih et al., 2013), a sub-group analysis was conducted. As described in the data analysis section, participants were classified into HS and NHS based on the average FSA of the control condition in each surface condition. Thirteen and seven participants were identified as NHS runners during level ground and downhill running respectively, paired *t*-tests between CON and MAX were conducted to compare FSA and impact loading in the two sub-groups (Table 6.5). No difference was found in either group of runners during level ground running regarding FSA. HS runners were found to run with a smaller FSA, trending towards a NHS, while downhill running in MAX; such difference was not observed in the NHS runners. The reduced FSA in HS runners could be explained by the flat midsole design, lowering the difference in stack height between the heel and the forefoot. Previous studies suggested that a lower heel-to-toe drop could promote a MFS landing in HS runners (Horvais and Samozino, 2013; Zhang et al., 2016b). Reductions in FSA have previously been observed in both overground and treadmill running, with the change in heel-to-toe drop from 8 mm to 0 mm (Chambon et al., 2015). For studies on MAX, a recent study reported an immediate reduction of FSA in a group of HS runners upon switching to MAX (Agresta et al., 2018). They used a different type of MAX with a 0 mm heel-to-toe drop, yet they found that all runners maintained a HS pattern despite the reduction in FSA when changing from their original running shoes to MAX, and no further reduction was observed after a four-week adaptation. In our study, the heel-to-toe drop of the MAX model (5.0 mm) was smaller than the CON model (9.2 mm), the stack height difference might be able to explain the reduce FSA in HS runners, but similar to Agresta *et al.*'s study, the reduction was not sufficient to induce a change in the footstrike pattern.

Another biomechanical parameter measured in this study was the impact loading. Based on the manufacturer's claim on better protection, we hypothesized a lower impact loading in MAX. However, no significant difference was found in the loading rates during level ground running and VILR during downhill running was even found to have higher in MAX (105.4±24.8 BW/s) compared to CON (94.5±24.5 BW/s). This increase in VILR when running downhill with MAX was also observed in HS runners. In fact, similar findings have also been reported previously; impact loading was measured in footwear of different amount of midsole cushioning and density. Although most of the previous studies only compared conventional footwear models, similar loading rates between midsoles of different densities have been reported (Chambon et al., 2014; Clarke et al., 1983; Nigg et al., 1987). Similar to our finding of increased VILR during downhill running, Sinclair *et al.* also observed such a trend in MAX during level ground running (Sinclair et al., 2016a). Although an explanation to the observation was not provided by the group, Baltich *et al.* has previously proposed that runners might increase their lower-limb joint stiffness when running in shoes with the softer midsole (Baltich et al., 2015). The assumption that additional cushioning provided by MAX can reduce external impact forces is therefore not convincingly supported by previously cited work and this present study.

There was a significant interaction between footwear condition and inclination for comfort, indicating that the comfort perceived between the two footwear models were affected by the running surface inclination. Pairwise-comparison on the comfort score on level ground revealed no significant difference, but MAX was rated with a significantly higher comfort score when being worn during downhill running. Comfort was suggested to be subjective (Slater, 1985), and it was not surprising that comfort would be influenced by external factors. Perceived comfort was previously reported to be different depending on the activity being conducted (Miller et al., 2000; Mills et al., 2011). Miller *et al.* compared three pairs of footwear when participants were standing, walking and running (Miller et al., 2000). They found that the average comfort ratings of each shoe were different in different activities, the same pair of shoes were rated less comfortable in a running trial compared to standing and walking. It is possible that the difference in the running surface would change the perception of runners, and the additional cushioning in MAX could only enhance the comfort during downhill running.

Another interesting observation in this study was the enhanced comfort and increased VILR found in runners running downhill with MAX. Even though a regression was not conducted on comfort and impact loading, our result did not support that shoes with better shock attenuation would consistently increase comfort. Indeed, it is still unknown as to what gives comfort in a pair of running shoes. Results from a previous study put a series of kinetic parameters and plantar pressure distribution during running to a test, none of which were found to be sufficient to predict the perception of comfort in runners (Dinato et al., 2015). Therefore, it is highly possible that comfort was influenced by subjective judgments and our next study was designed to investigate the self-perceived comfort by using a deceptive design, assessing the effect of price and information used to describe a pair of footwear on both comfort and running biomechanics.

Table 6.5 Biomechanical data and comfort score (mean ± SD) between conventional footwear (CON) and maximalist (MAX) during level ground and downhill running for heelstrike (HS) and non-heelstrike (NHS) runners

Level ground

	Runners with HS (n=14)				**Runners with NHS (n=13)**			
	CON	**MAX**	***P*-value**	**Cohen's *d***	**CON**	**MAX**	***P*-value**	**Cohen's *d***
FSA (º)	14.1 ± 4.7	12.2 ± 5.1	0.434	0.40	2.2 ± 3.5	2.8 ± 4.4	0.658	0.17
VALR (BW/s)	64.5 ± 13.3	62.6 ± 13.6	0.612	0.14	54.2 ± 16.6	54.0 ± 13.2	0.982	0.01
VILR (BW/s)	75.0 ± 15.3	78.4 ± 17.9	0.337	0.22	72.2 ± 18.6	72.3 ± 16.1	0.979	0.01

Downhill

	Runners with HS (n=20)				**Runners with NHS (n=7)**			
	CON	**MAX**	***P*-value**	**Cohen's *d***	**CON**	**MAX**	***P*-value**	**Cohen's *d***
FSA (º)	18.8 ± 5.4	15.7 ± 6.1	0.006*	0.57	-4.3 ± 6.9	3.5 ± 6.7	0.104	1.13
VALR (BW/s)	80.0 ± 19.5	84.5 ± 17.7	0.332^{+}	0.23	67.3 ± 29.4	88.4 ± 31.9	0.279	0.72
VILR (BW/s)	95.8 ± 24.3	104.0 ± 22.4	0.060	0.34	90.6 ± 26.6	109.2 ± 32.4	0.309	0.70

FSA, Footstrike angle; VALR, Vertical average loading rate; VILR, Vertical instantaneous loading rate; BW, Body weight

P-values were calculated using paired *t*-test unless otherwise specified. HS and NHS runners were classified based on the CON running condition.

$^{+}$ *p*-value calculated using Wilcoxon signed-rank test due to non-normally distributed data

* $p < 0.05$

6.2.5 Conclusion

The additional cushioning provided by MAX does not appear to change the footstrike pattern, nor reduce the impact loading experienced by runners. Our findings even suggested an increased impact loading during downhill running. Furthermore, a better perceived comfort was reported when participants were running downhill with MAX, but not during level ground running.

6.3 Footwear comfort

6.3.1 Perception of comfort and running biomechanics

The increase in the running population has led to a higher demand in running shoes. A large number of recreational runners select their shoes based on subjective comfort, which was suggested to be related to the injury development and athletic performance of a runner (Meyer et al., 2018; Miller et al., 2000). Despite the aggressive advertising and marketing strategies by sporting brands, a universally comfortable pair of shoes could not be found in the market. Considering that comfort is highly subjective (Slater, 1985) and hard to quantify, Mündermann *et al.* has developed a method using a series of VAS to assess general footwear comfort (Mündermann et al., 2002). The method was found reliable with high intraclass correlation coefficients (ICC=0.799) between all subjects for nine sessions. In a recent study, four footwear conditions with different midsole stiffness and cushioning technologies were tested (Dinato et al., 2015). The results showed that none of the kinetics parameters, material stiffness or pressure distribution, were able to predict the perception of comfort in runners. Our study in section 6.2 also found a higher impact loading in the footwear condition that was rated more comfortable, suggesting that the shock attenuation property might not be a major factor in determining comfort. Although the relationship between comfort and footwear construct has been profoundly investigated, there is currently no consensus on what gives comfort in a pair of running shoes.

Deceptive messages used in advertisements or product description, especially those that implied-superiority against other brands, could mislead customers whether intended or not (Snyder, 1989). A study which focused on the effects of deceptive advertising regarding athletic footwear suggested that user caution could be affected by misleading messages (Robbins and Waked, 1997). A false sense of security could be induced by the deceptive message or the price information provided to the runner prior to shoe testing. However, the biomechanical variables were suggested to be more inert. Adjustments to the running pattern has been observed in runners when shoe cushioning deteriorates due to continued usage (Kong et al., 2009). These adaptation strategies were suggested to help maintain a constant external load. Another study found that the VALR differed by less than 7.4% among four shoe models with different cushioning technology (Dinato et al., 2015). The mean PPA measured at the tibia, which is a surrogate of impact loading (Lafortune and Lake, 1995), were found within 9 to 10 g for all shoe types tested, suggesting that the human body would respond accordingly to changes in impact within the "kinetic bandwidth" (McNair and Marshall, 1994). This particular study also measured kinematic parameters while running in these four footwear models. Upon IC, the ankle joint angle was similar, i.e. within $80^{-}85^{o}$, in all shod conditions despite the difference in stiffness. This suggested that the running kinetics and kinematics were rather resistive to changes among different footwear conditions. Previous studies suggested proprioception while running in a different pair of shoes would not alter running kinematics when no additional information was given (Willy and Davis, 2014), implying potential cognitive contributions behind the changes we observe.

It is important to note that previous studies only investigated how different footwear altered runners' perception and the biomechanical variables, without addressing the neuro-physical and psychological factors. In a recent wine study which studied how context could alter perception and value, information provided to participants was found to affect the sensory experience (Schmidt et al., 2017). Apart from a higher pleasantness rating, the wine which claimed to be more expensive were able to modulate the tasters' experience on a neural level. Also, an interesting study by Hennig and Schulz has suggested that the subjective judgments on running shoe quality was highly dependent on the brand, and the same shoe model was rated differently under blinded and non-blinded situations (Hennig and Schulz, 2011). The findings of the mentioned studies suggest the potential placebo effect of price cues and footwear description on comfort, indicating psychological aspects and motivational process of valuation could also play an important role in the a runner's perception. *The difference in the perception of comfort and running biomechanics when runners were presented with the same pair of footwear with different descriptions remains unknown.*

Hence, the objective of this study was to use a deceptive study design to investigate the self-perceived comfort and the running biomechanics in the same pair of running shoes. The independent variable of this study was the shoe descriptions provided to the runners, i.e. deceptive message describing a pair of running shoes made to appear different in comfort design and cost. A hypothesis was established, that there would be a within-subject difference in the comfort perception, but no within-subject differences in running biomechanics when running in the same pair of shoes.

6.3.2 Methods

6.3.2.1 Participants

An estimation of the sample size was based on a previous study on footwear comfort (Miller et al., 2000). Recreational runners were recruited from local running clubs, inclusion criteria set for this study included: 1) within the age of 20-50, 2) regular shod runner with more than 8 km per week, 3) with treadmill running experience in the past three months, and 4) shoe size within the range specified in section 6.3.2.2. Participants with injuries in the lower extremity in the past six months were excluded. The experimental procedures were reviewed and approved by the institutional review board and written consent was obtained from each participant before the experiment.

Originally, a total of 18 recreational runners were recruited. Two participants were excluded because of a failed deception, and we did not analyze the data from another participant as he reported previous running experience in the test shoe model upon the completion of the test. The mean and SD of the characteristics of the remaining 15 runners are presented in Table 6.6.

Table 6.6 Characteristics of participants

Characteristics	**Mean and SD**
Gender	9 males, 6 females
Age (year)	31.9±11.0
Weight (kg)	60.2±7.6
Height (m)	1.70±0.10
Running experience (year)	5.9±1.9
Running speed (ms^{-1})	2.22±0.13

SD, Standard deviation

6.3.2.2 Test shoes

Participants were instructed to complete four running trials. The first and the third trials acted as control trials, in which the participants were provided with their usual running shoes. The second and the fourth trials were experimental trials, in which the same pair of neutral running shoes (ARHL002, LiNing, Beijing, China) was worn as both Shoe A and Shoe B (Figure 6.2). This experimental setup was designed to improve reliability by eliminating the effect of the preceding footwear condition (Mündermann et al., 2002). The order of the two shoe conditions was randomized. The information of Shoe A and Shoe B was introduced by written descriptions as follows.

Shoe A: HKD 400 (USD 50); regular running shoe model; designed for distance running; available in the market

Shoe B: HKD 1,200 (USD 150); latest shoe model designed to maximize comfort; highly expensive material used; yet available in the market

Figure 6.2 Running shoe model used in this study. The magnetic clips were used to ensure tightness between trials.

6.3.2.3 Data collection

The participants were given five minutes of warm-up on a treadmill (Wood and Kipp, 2014) and selected a testing speed that was similar to their usual training speed. The sequence and description of shoes worn were provided to participants before the first running trial. In order to eliminate the subjective visual perception, participants were blindfolded and the test shoes were fit by a single researcher. The tightness of the shoe laces between trials was controlled by a magnetic clip-on device (Zubits, Danville, CA, USA) (Figure 6.2). With an overhead safety harness supported, participants were asked to hold on to the side-rail within arm-length of the instrumented treadmill (Force-sensing tandem treadmill, AMTI, Watertown, MA, USA) on the right at the start of each trial. Speed was gradually increased upon verbal consent from the participant until the predetermined testing speed. A four-minute adaptation period were set (Divert et al., 2005), participants displayed a stable running gait after the adaptation period. Afterwards, kinetics and kinematics data were collected for one minute. Participants were told to hold onto the side-rail again when the treadmill decelerated to a complete stop. Immediately after each running trial, participants were asked to rate the comfort level of the test shoes based on the running trial using the comfort measurement tool (Mündermann et al., 2002). Each trial was separated by a washout period of 15 minutes (Bishop et al., 2006).

Perception of comfort for each footwear condition was assessed using a MATLAB (The MathWorks, Inc, Natick, MA, USA) program, nine VASs were displayed on a hand-held tablet one after another

(ThinkPad 8, Lenovo, Beijing, China). A comfort scale of 100 mm in length was displayed on the screen with the left-most side labelled “not comfortable at all”, and the right-most labelled “most comfortable condition imaginable”. An information sheet was provided to the participants, guiding participants to fill out each VAS. (Appendix II) The comfort measure consisted of nine domains, including “overall comfort”, “forefoot cushioning”, “heel cushioning”, “arch height”, “heel cup fit”, “shoe heel width”, “shoe forefoot width”, “shoe length” and “medio-lateral control”. This method has been validated and shown to give reliable measurements for footwear comfort (Mündermann et al., 2002).

6.3.2.4 Data analysis

Comfort ratings in all nine domains were converted and presented as a score between 0 and 100, where a score of 100 indicates the best comfort level.

Three-dimensional running kinematics was recorded during all running trials using reflective markers placed on the lower extremity of the participant. Sixteen markers were placed over the anatomical landmarks following a validated model described in section 2.2 (Kadaba et al., 1989; Winter, 2009). During the data collection period, marker trajectories were collected at 200 Hz using an 8-camera motion capturing system (VICON, Oxford, UK) positioned around and focused on the participant. The left lower limb was selected as the test limb. Marker trajectories were filtered using a 12 Hz cut-off low-pass recursive Butterworth filter (Sinclair et al., 2016a). Lower-limb joint angles of the test limb were computed using anthropometry data, body mass and body height of each subject for subject-specific calculation based on the mentioned model. Ankle and knee joint angle during IC in the sagittal plane and the peak knee flexion angles that occurred during the stance and swing phase were extracted and averaged across 20 footfalls.

Time of IC was determined from the GRF, contact time and the percentage of stance within one gait cycle was calculated and averaged from the last 20 gait cycles in each shoe condition (Padulo et al., 2012). Cadence was measured as the number of steps within the one-minute data collection period.

Vertical GRF was sampled at 1,000 Hz by the treadmill, it was filtered and processed using customized MATLAB codes using a low-pass, fourth-order Butterworth filter with cut-off frequency set at 50 Hz, and normalized by participants' body weight. VALR and VILR were obtained by the method described in a previous study (Crowell and Davis, 2011), detailed in section 2.3. Both VALR and VILR were averaged across the last 20 footfalls of the test limb in each shoe condition.

An additional measure to describe the similarity of the kinematics between footwear conditions was adopted. Lower-limb kinematic curves were time-normalized to 100 percent by gait cycle. The trend symmetry method proposed by Crenshaw and Richards was used to assess the similarity in the kinematic curves between the experimental shoe conditions for each participant (Crenshaw and Richards, 2006). Four variables, including trend symmetry, range amplitude, range offset and phase offset were calculated for all three planes of motion for the hip, knee and ankle joint. A trend symmetry value of 100% indicates perfect symmetry. The range amplitude value quantifies the difference in the range of motion between two curves, expressed as a ratio of Shoe B to Shoe A. Range offset was calculated by subtracting the average of Shoe B from Shoe A. A positive phase offset implies that the curve of Shoe B was shifted forward relative to the Shoe A curve.

6.3.2.5 Statistical analysis

All dependent variables were tested against a normal distribution by using separate Shapiro-Wilk tests. Paired t-tests were used to compare the differences in comfort score and running biomechanics between Shoe A and Shoe B. Cohen's *d* was calculated to evaluate the effect size between the two shoe conditions. All statistical tests were performed by SPSS software (Version 20, SPSS Inc., Chicago, IL, USA), with alpha set as 0.05.

6.3.3 Results

Participants reported significantly greater comfort in Shoe B than Shoe A (*p*=0.011, Cohen's *d*=0.70). Regarding the specific aspects related to footwear comfort, the comfort rating for medio-lateral control (*p*=0.001, Cohen's *d*=1.07) and arch height (*p*=0.014, Cohen's *d*=0.81) were significantly higher (Table 6.7).

Selected joint angles, temporal spatial parameters and loading rates are presented in Table 6.8. Ankle and knee joint angles at IC, peak knee angle during stance and peak knee angle in the sagittal plane during swing were all found to be comparable between Shoe A and Shoe B ($p>0.597$, Cohen's $d<0.09$). The joint angle profile curves were similar between the two shoe conditions (Figure 6.3), as justified by the trend symmetry value for all kinematic curves. The average trend symmetry value for all joints in the the three planes was 97.8% (Table 6.9). The average range amplitude was 1.003 and the average range offset was only 0.048°, indicating a highly comparable range of motion at each joint and minimal difference within the gait cycle between different shoe conditions. The phase offsets were all less than 0.5% of a gait cycle.

For temporal spatial parameters, both percentage stance ($p=0.562$, Cohen's $d=0.10$) and cadence ($p=0.884$, Cohen's $d=0.03$) were similar between Shoe A and B (Table 3). Regarding running kinetics, VALR ($p=0.735$, Cohen's $d=0.03$) and VILR ($p=0.312$, Cohen's $d=0.08$) were invariant between Shoe A and Shoe B (Table 3).

Table 6.7 Mean and standard deviation (SD) of perceived comfort when running in the two deceptive footwear conditions

Comfort categories	**Shoe A**	**Shoe B**	***P*-value**	**Cohen's *d***
	Mean and SD	**Mean and SD**		
Overall comfort	66.4±16.7	76.2±10.6	0.011*	0.70
Heel cushioning	71.6±13.8	76.0±13.6	0.125	0.32
Forefoot cushioning	67.9±20.9	74.8±13.3	0.107	0.39
Medio-lateral control	61.7±16.5	77.1±12.0	0.001*	1.07
Arch height	64.0±17.6	76.8±13.9	0.014*	0.81
Heel cup fit	64.3±17.5	71.7±20.4	0.267	0.39
Shoe heel width	68.1±15.8	72.7±16.5	0.310	0.28
Shoe forefoot width	64.9±23.2	73.8±15.1	0.208	0.45
Shoe length	67.5±16.5	75.6±12.4	0.067	0.55

All comfort values were converted to a scale from 0-100, where 100 indicated best comfort level.
* $P < 0.05$

Table 6.8 Mean and standard deviation (SD) of sagittal joint angles, temporal spatial parameters and kinetics variables when running in the two deceptive footwear conditions

Variables	**Shoe A**	**Shoe B**	***P*-value**	**Cohen's *d***
	Mean and SD	**Mean and SD**		
Ankle joint angle at IC# (°)	85.9±5.3	85.4±5.6	0.597	0.09
Knee joint angle at IC (°)	16.6±6.6	16.2±5.8	0.679	0.06
Peak knee flexion angle during stance (°)	41.0±6.9	40.9±5.4	0.901	0.02
Peak knee flexion angle during swing (°)	81.1±13.0	81.6±12.3	0.665	0.04
Percentage stance (%)	38.6±3.6	39.0±4.3	0.562	0.10
Cadence (steps/min)	165.2±11.4	164.9±11.8	0.884	0.03
VALR (BW/s)	46.6±17.0	47.1±20.9	0.735	0.03
VILR (BW/s)	56.7±18.4	58.3±22.4	0.312	0.08

IC, Initial contact; BW, body weight; VALR, vertical average loading rate; VILR, vertical instantaneous loading rate

Ankle angle value less than 90° indicates dorsiflexion

Table 6.9 Mean and standard deviation (SD) of trend symmetry measures for the hip, knee and ankle joint in the sagittal, frontal and transverse plane

		Trend symmetry (%)	Range amplitude	Range offset (°)	Phase offset (%)
		Mean and SD	Mean and SD	Mean and SD	Mean and SD
Hip	Sagittal	99.7±0.3	1.004±0.032	0.624±3.000	0.429±1.089
	Frontal	98.9±1.0	1.019±0.163	0.733±2.118	0.071±0.917
	Transverse	96.3±5.0	0.970±0.113	0.764±2.534	0.357±1.082
Knee	Sagittal	99.6±0.3	1.029±0.041	-1.218±2.295	0.357±0.842
	Frontal	98.4±1.6	0.962±0.158	1.348±4.844	0.286±0.914
	Transverse	98.2±2.8	0.992±0.107	-2.926±4.485	0.143±0.864
Ankle	Sagittal	99.6±0.3	1.012±0.064	0.466±1.785	0.071±1.207
	Frontal	99.0±0.6	1.033±0.120	-0.026±0.686	0.000±0.784
	Transverse	99.0±0.6	1.002±0.093	-0.199±1.069	0.000±0.784
Average		**98.7±1.4**	**1.003±0.099**	**-0.048±2.535**	**0.190±0.943**

A trend symmetry value of 100% indicated perfect symmetry. A value of range amplitude larger than 1.0 indicated a larger range of motion for Shoe B. A positive range offset value indicated a larger mean value in Shoe B. A positive phase offset indicated the Shoe B curve was shifted forward relative to the Shoe A curve.

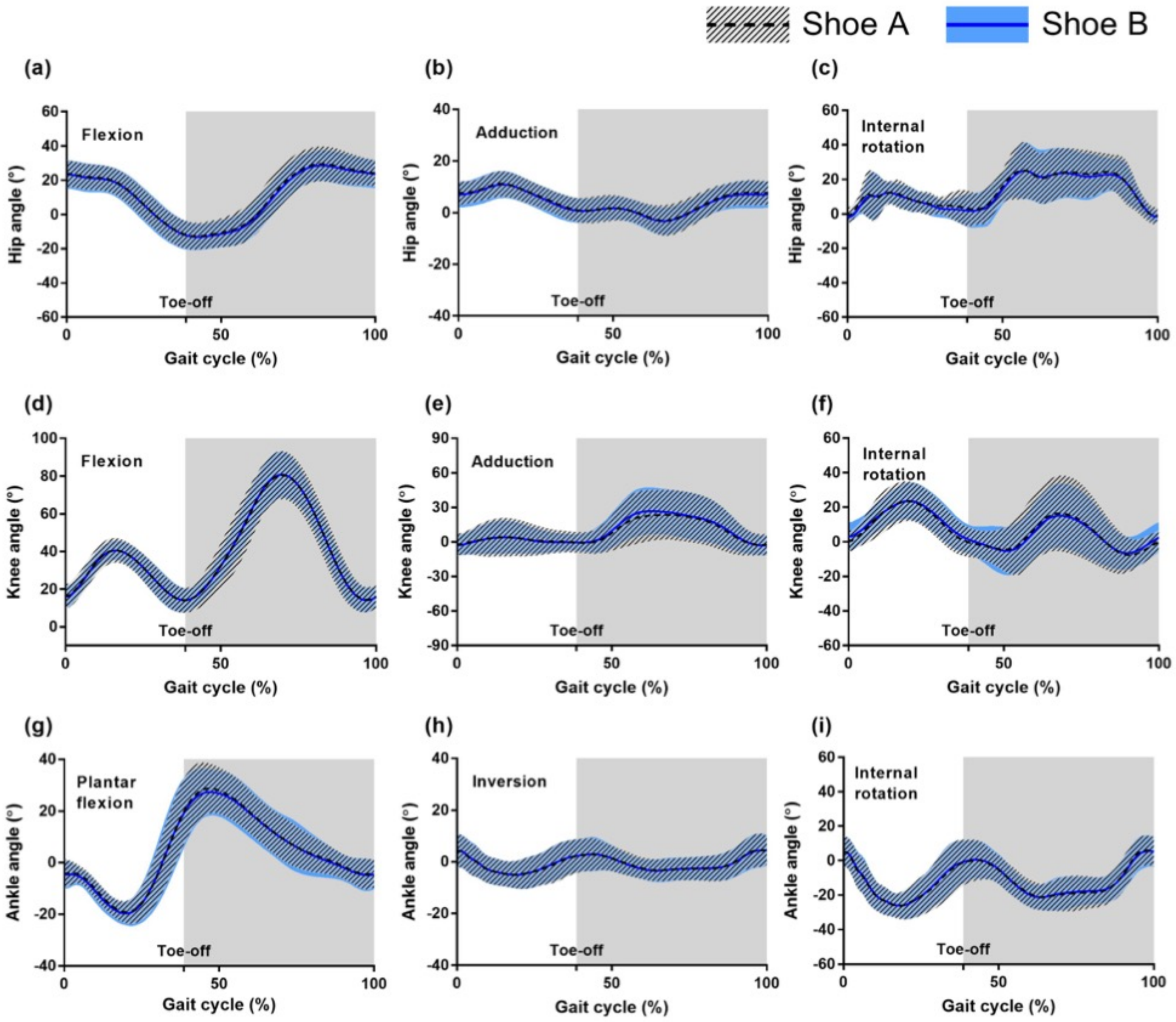

Figure 6.3 Hip, knee and ankle joint angle profiles (Mean and SD) in the sagittal (a, b and c), frontal (d, e and f) and transverse (g, h and i) plane while running in Shoe A and Shoe B

6.3.4 Discussion

This study examined the effects of deceptive footwear conditions on subjective comfort, joint kinematics, temporal spatial parameters and impact loading while running in the same pair of shoes. Our results demonstrated that alternative price cues and shoe descriptions could affect the perceived comfort, but the difference in the perception did not necessarily change the running biomechanics.

Previously, a large number of shoe models has been tested and found to alter the running biomechanics. For instance, Sinclair *et al.* compared MIN and MAX, which differed in the amount of cushioning to CON footwear (Sinclair et al., 2016). The results showed that impact loading, as measured by VILR and PPA, were significantly higher in MIN than in MAX or CON. On top of the changes in kinetics, larger internal rotation in the tibia was also observed in MIN. Another study conducted by Cheung and Ng compared a motion control footwear design with its neutral equivalent, motion control shoes were able to reduce excessive rearfoot movement in a group of runners with excessive foot pronation (Cheung and Ng, 2007). In the present study, neutral running shoes were provided to eliminate changes to running biomechanics induce by specific types of footwear. In addition, a running trial using participants' usual shoes was conducted prior to each running trial in the test shoe. This arrangement was put forward by Mündermann *et al.* for a reliable shoe comfort measurement using VAS (Mündermann et al., 2002). The control condition using participants' regular running shoes served as the source for comfort comparisons, as participants tend to subjectively compare the features of a shoe with previous experience (Nunnally and Bernstein, 1994).

According to our results, the subject-perceived comfort of the footwear was different in the same pair of running shoes being described differently. The overall comfort was perceived to be better in the pair of shoes described to be costlier and constructed with high technology materials, suggesting a potential bias could be induced by such false claims. Miller *et al.* have suggested that perception of comfort could be affected collectively by mechanical, neuro-physiological and psychological attributes (Miller et al., 2000). We presented the same pair of shoes to runners, deceiving them with difference in price and design technologies. Such information acted to alter the comfort perceived by influencing a runner psychologically. In our experiment, we did not provide details of the modification made to the shoe to increase comfort, nor the materials we used. Our message was designed to provide only a general description and would be interesting to find if runners rated specific areas to be more comfortable. Although not all eight of the comfort-related specific aspects rated by runners were statistically different, most of the runners were able to point out specific discomfort using the series of VSA. A similar bias on subjective judgment has previously been described in Henning *et al.*'s study, in which they found that a low cost running shoe model was rated as well as the known athletic brand when runners were blinded, and branded shoes were rated better when runners were aware of the brand (Hennig and Schulz, 2011). These interesting results suggested that runner's perception of comfort was susceptible to deception, by factors such as branding, cost and vague description.

The kinematic curves presented in Figure 6.3 were averaged across participants for each shoe condition, and all joints in all planes were within one standard deviation of the other condition. Even so, as the figure presented only the group average, the trend symmetry method was used in addition to quantify the within-subject differences. Crenshaw and Richards suggested a trend symmetry value of 95% or above indicated similar kinematic curve trend based on a normal population (Crenshaw and Richards, 2006). This method has been used by Fellin *et al.* in comparing kinematic curves between overground and treadmill running (Fellin et al., 2010). Values measured in this study were all above 95%, indicating similar running kinematics in shoes of different comfort levels.

A number of temporal spatial parameters and discrete joint kinematics were analyzed in this study. These variables were selected based on their relationship with running performance. Hip, knee and ankle joint kinematics were found to be related to running speed (Bishop et al., 2006; McNair and Marshall, 1994); and the cadence was associated with energy consumption and running economy (Wunsch et al., 2016). Although it was speculated that subjective comfort might play a role in affecting athletic performance (Miller et al., 2000), no relationship between comfort and the measured variables related to performance could be observed in this study.

Significant associations have been demonstrated between loading rates and RRIs from our study presented in chapter 3. A high loading rate would increase the risk of running related overuse injuries, including patellofemoral pain (Cheung and Davis, 2011), plantar fasciitis (Pohl et al., 2009) and tibial stress fractures (Crowell and Davis, 2011; Pohl et al., 2008). It has been suggested that runners would subconsciously subject themselves to a increased loading when running with more expensive shoes, thus increasing the risk of injury (Robbins and Waked, 1997). Clinghan *et al.* have investigated the comfort in shoes at different prices, yet the most expensive pair did not provide better cushioning nor rated to be more comfortable than the others when runners were unaware of the footwear conditions (Clinghan et al., 2008). The present study was designed to eliminate the differences in footwear and investigate the effect of comfort alone, our results suggested that loading rates were not affected by the difference in the perception of comfort. Our findings agrees with the suggestion by Shin *et al.* that biomechanical running assessments, such as kinematics and kinetics measurements, were better indicators for shoe selection rather than only considering the shoe type (Shih et al., 2013), and especially not based on comfort alone.

6.3.5 Conclusion

Runners' perception on footwear comfort could be influenced by the price and context describing the footwear, yet difference in comfort alone might not lead to changes in running biomechanics. This disassociation between perception and running biomechanics suggest that runners should not consider comfort as the only factor for running shoe selection.

CHAPTER 7

GENERAL DISCUSSION

7.1 Overview

The results of this thesis provide evidence to support the effect of running gait retraining as a clinical tool for prevention of running injuries. In addition, the thesis aims at evaluating a gait retraining protocol which promotes MFS landing. The evaluation was based on the changes to running biomechanics related to various running injuries. Furthermore, we examined footwear properties that were previously found to affect the footstrike pattern and impact loading, providing insights into the effect of external factors on the running biomechanics.

In Chapter 3, we investigated the effect of a gait retraining protocol by comparing the change in impact loading and occurrence of injury. This large-scale RCT involving 320 novice runners was designed to connect the reduction in impact loading through gait retraining with the injury risk in runners. The intervention group was provided with an eight-session visual feedback gait retraining, while the control group went through the same training schedule without feedback. The visual feedback gait retraining was found effective in reducing impact loading, and subsequently lead to a reduction in RRI occurrence in the intervention group by 62% as compared with the control group. To our best knowledge, it is the first clinical study to provide evidence to support gait retraining for injury prevention by impact loading reduction, which is also the foundation for the hypothesized biomechanical modification brought by the main study in Chapter 4 and 5.

An extensive evaluation of a real-time feedback gait retraining program that promotes MFS landing was presented in Chapter 4 and 5. Real-time footstrike information was provided to RFS runners, they were asked modify their running gait to achieve a MFS landing. Modification of footstrike pattern has previously been shown to reduce the impact loading, and subsequent health benefits has been proposed by researchers. Although we did not observe a complete transition of footstrike pattern towards MFS, we observed a FSA reduction towards the cut-off angle between RFS and MFS. Surprisingly, trained runners did not exhibit changes in loading rates, which is a clinically relevant biomarker of RRI risk. Chapter 5 focused on the two practical concerns of the training effect, sustainability and inter-limb skill transfer. The training effects put forward in Chapter 4 were further assessed on both the trained and the untrained side and one-month after the runner returned to his/her own training schedule. Our training provided visual feedback to one of the limbs only; footstrike information of the other side was not available. Reduction in FSA was found in both the trained and untrained limbs, and such changes in the FSA could be maintained in the one-month follow-up. The sustainability of the effect is of practical significance for injury prevention, as the modifications are only meaningful if the effect could last.

Gait retraining aims to modify running biomechanics through motor re-learning, while other external factors has also been found to affect impact loading and footstrike pattern. Chapter 6 is an extension to the main study; investigations on the effect of extreme midsole cushioning and perception of comfort on running biomechanics were discussed. We found that the additional cushioning provided in MAX footwear provided more perceived comfort but also induced a greater VILR during downhill running, potentially exposing runners to a higher risk of RRI. Perception of footwear comfort was suggested to be susceptible to the price and description provided, but the difference in the perception alone was unlikely to change the running biomechanics.

In summary, this thesis provides an extensive evaluation on two approaches in modifying the running posture, i.e., gait retraining and footwear. We have presented its evidence and justification and our findings could seed future gait retraining studies to optimize the protocol and mitigate the risk of RRIs.

7.2 Effect of gait retraining to mitigate risk of running-related injuries

Although the development of RRIs were considered multi-factorial (van der Worp et al., 2016; van Gent et al., 2007), extensive scientific evidence has connected high impact loading and various types of RRI (Davis et al., 2016; Pohl et al., 2008). Attempts to reduce impact loading have therefore been a research focus for years.

Researchers in the field of biomechanics and rehabilitation have proposed the idea of using gait retraining to correct and adjust improper running form (Davis and Futrell, 2016). Its effectiveness on relieving pain and symptoms in injured runners has been demonstrated. Runners suffering from patellofemoral pain (Cheung and Davis, 2011; Noehren et al., 2011; Roper et al., 2016; Willy et al., 2012), chronic exertional compartment syndrome (Diebal et al., 2012, 2011) or anterior exertional lower leg pain (Breen et al., 2015) were shown to benefit from running retraining, and pain level was reduced after modifying their gait.

Impact loading is a modifiable risk factor of RRI. Gait retraining has been proposed as a clinical tool to reduce impact loading in healthy runners as well (Cheung et al., 2018; Crowell and Davis, 2011). Recent gait retraining studies have shown the potential benefit of gait retraining, and our study presented in Chapter 3 extends our understanding of the training outcomes.

Our results in the large prospective RCT presented in Chapter 3 suggested that a two-week lab-based gait retraining was effective in lowering the impact loading in a group of novice runners. Differences in effect size and sustainability were observed between our study and other past studies conducted by various research groups (Clansey et al., 2014; Crowell and Davis, 2011), and it is plausible that the difference is related to the variation in training target, training speed, method of feedback delivery and the type of feedback provided. Our study was not designed to compared between training protocols. Instead, our training protocol was designed to maximize the training effects so that runners may maintain the modified gait in a natural training environment during the follow-up period.

Regarding the effectiveness of the gait retraining in mitigating RRI risk, we observed a 62% lower rate of RRIs at the twelve-month follow-up compared to the control group. This study could be a foundation for translating various attempts for reduction in impact loading to the practical significance of protecting runners from RRIs.

7.3 Effect of gait retraining to promote midfoot landing in runners

Footstrike pattern has also been suggested as a contributing factor of RRI (Daoud et al., 2012; Goss and Gross, 2012). The RFS, which is the most prevalent footstrike pattern among recreational and elite runners (Cheung et al., 2016b; Hasegawa et al., 2007), has been shown to induce higher impact loading than a MFS and FFS (Lieberman et al., 2010), and could subsequently expose the runners to a higher rate of overuse injuries. Footstrike pattern modification has therefore been suggested as potential methods to protect runners from RRIs. Previous studies which modify the footstrike pattern of habitual RFS runners to MFS or FFS found the training favorable in managing pain in injured runners, improving performance and reducing loading rates. However, there has been disputes against such a change, mainly due to the lack of evidence in support of the long-term effect on injury and the increase in injury risk in the ankle plantarflexors and the Achilles tendon when running with a FFS (Hamill and Gruber, 2017; Kulmala et al., 2013). Switching to a MFS has therefore been suggested as a more ideal footstrike pattern (Altman and Davis, 2009).

The potential to use footstrike information as a feedback for gait retraining was explored in Chapter 4 and 5. We found significant reduction in the FSA, but a complete transition has not been observed in the trained runners. Achieving a MFS, as compared to RFS or FFS, was considered more difficult, and some runners could have trouble switching to a MFS without overcorrecting to a FFS. An adjustment to the training protocol might be able to give a bigger change towards a MFS landing.

In Chapter 5, we have evaluated the carryover effect of gait retraining to the untrained limb. Similar to other previous studies (Cheung and Davis, 2011; Clansey et al., 2014; Crowell and Davis, 2011), our study adopted a single-limb feedback design. We found no interaction between side and training, indicating the change in FSA on the two limbs was not affected by single-side feedback provided. Although the mechanism behind the skill transfer has not been investigated in our study, our findings would be useful for further feedback design, especially with in-field gait retraining, where resources are limited and a simple design is favored (Willy et al., 2016).

Regarding the sustainability, we found that runners were able to maintain the modified gait pattern one month after the training. This reflected the internalization of the newly learnt gait pattern and runner could naturally execute the modified pattern without having to rely on feedback (Barrios et al., 2010). Even though we did not perform longer follow-up biomechanical assessments, it is still possible that the training effect could be maintain, as seen in other case studies with three-month or one-year follow-up (Cheung and Davis, 2011; Davis and Futrell, 2016; Diebal et al., 2011).

Surprisingly, there was a large discrepancy between the changes in impact loading after training, contradictory to our hypothesis a reduction was not observed. Giandonlini *et al.* has reported significant reduction in impact loading when habitual RFS runners were instructed to land with a MFS (Giandolini et al., 2013), however, the footstrike pattern was not measured during the running trials, it is possible that the runners ran with a FFS instead of a MFS. Similar deduction was also proposed by Altman and Davis (Altman and Davis, 2009). The inconsistency between participants we observed could be explained by the modulation of joint stiffness. Hamill *et al.* has previously suggested that the ankle and knee stiffness would change as the runner modify his/her footstrike pattern (Hamill et al., 2014). We found similar results in the knee joint stiffness. In addition, we also found a moderate correlation between the change in ankle stiffness and loading rate. Our results suggested that a less compliant ankle could result in increased impact loading after the training.

7.4 Effect of footwear on footstrike pattern and impact loading

Shoe manufacturers would base their claims on mechanical material testing using impactor device. This device could stimulate a footstrike with high impact velocity and the impact attenuation property could be measured. However, it has been argued that these material tests were not sufficient in reflecting the true effect of running shoes on the human body (Hennig et al., 1993), and there are differences between the results of material testing and biomechanical tests (Hennig, 2011). McNair and Marshall has tested four pair of running shoes which were found to have different shock absorption in material tests, the shock experienced by the runners were comparable despite the marked difference in the material stiffness (McNair and Marshall, 1994). In the first study in Chapter 6, we tested the impact loading of runners while running in a conventional shoe model and MAX. Difference in impact loading is a surrogate measure for difference in shock attenuation property between footwear (Fong Yan et al., 2013), and has a strong association with RRI (Davis et al., 2016). Contradictory to the claim of the manufacturers, the impact loading found in runners wearing MAX was not lower than in CON, and was even found to be higher when running downhill. Furthermore, the effect of MAX on FSA was difference between runners with different footstrike pattern, RFS runners were found to run with a smaller FSA in MAX while the mean FSA of Non-RFS runners was higher in MAX. There is a possibility that footwear would affect runners of various footstrike pattern differently, and even if certain type of footwear was found protective to specific runners, it may not be true for all runners.

As for the other study in Chapter 6, we observed that the context and price of footwear are sufficient to alter the perceived comfort in runners. Comfort is a major criterion for runners in selecting running shoes, as it was proposed to be related to fatigue, injury and performance in running (Meyer et al., 2018; Miller et al., 2000). Past studies reported inconsistent relationship between footwear comfort and physical parameters, such as shoe stiffness or plantar pressured during running (Dinato et al., 2015). Hennig and Schulz has suggested that the subjective judgments on shoe quality was dependent on the brand; footwear were rated differently under blinded and non-blinded situation (Hennig and Schulz, 2011). This suggested that comfort being so abstract, could be subjected to psychological factors. The results of our study has supported the idea that comfort was subjected to deceptive information, the more expensive shoe was rated more comfortable than the one, despite the two being exactly the same.

However, the biased perception on comfort does not lead to changes in running biomechanics. We did not find any difference in joint kinematics and impact loading between the same pair of shoes with subjective comfort differences. Running biomechanics were more inert to changes, and should therefore be considered for shoe selection.

7.5 Limitations

Several limitations should be considered in light of our findings presented in each Chapter, the limitations are detailed as follows:

1) A limitation common to all the studies was the treadmill-based gait assessments. The effect of gait retraining (Chapter 3-5) and footwear (Chapter 6) were evaluated on an instrumented treadmill. Treadmill-based gait assessments allowed researchers to standardize the testing environment and control the speed precisely, reducing the variance between conditions. However, running biomechanics between overground running and treadmill running were not exactly identical (Riley et al., 2008). The majority of recreational runners trains and competes overground; a treadmill-based assessment may limit the generalizability of our results. Even so, for our variables of interest, loading rates and FSA, the difference may not be substantial to our findings. Loading rates were found comparable (Riley et al., 2008) and FSA change induced by difference in heel-to-toe drop (0 mm to 8 mm) were found to follow a similar trend (Chambon et al., 2015) when assessed overground and on a treadmill. Our findings could still provide useful information as treadmill-based assessments were still considered a valid evaluation method by many research groups.

2) Some of our studies were underpowered; the sample size was too small to draw conclusions that there was no difference between conditions. *A priori* power analyses were performed for the studies in Chapter 4 and 6. In Chapter 4, preliminary data was collected and applied in the sample size estimation. Based on our hypotheses, the trained runners would be able to reduce both FSA and VALR upon training. The estimated sample size of 12 was based on the assumption that both variables would change concurrently. Based on the results of 14 participants,

FSA was found to be significantly reduced, yet no significance difference was found for VALR between Pre- and Post-training conditions. The variability of VALR between participants was large, but not for FSA, creating a mismatch of study power between the two variables. Post-hoc power analysis was conducted, with power equals to 0.256 for VALR. To achieve a power of 0.8, this study would require at least 54 runners. This mismatch between *a priori* power and post-hoc power could be explained by the inconsistency of the effect of training on participants. While there was a significant difference Pre-FSA and Post-FSA, the result of VALR was found contradictory to our hypothesis. This suggested that FSA might not be the only factor which governs impact loading. Although the study in its current form was underpowered to detect statistical significant difference, we could still observe a large discrepancy between participants, which could be clinically meaningful. The change in VALR before and after the training ranged from a 46.13 BW/s reduction to a 26.06 BW/s increase, this indicates a large variance in the training effect between participants. Modifying the feedback type or personalizing the gait retraining could be considered more meaningful than to simply increase the sample size based on the current results.

The statistical power in the study on MAX in Chapter 6 ranged between 0.06 and 0.09 for the kinetic variables measured during level surface running, the effect size was smaller than 0.11. Post-hoc sample size calculated determined that it is necessary to recruit over 1,600 runners to achieve a power of 0.8, which would be non-viable, and the effect size would still be small and considered practically trivial (Cohen, 1988; Sawilowsky, 2009).

3) For our gait retraining studies (Chapter 3-5), the training program can only be delivered inside the laboratory. The use of sophisticated laboratory

equipment has limited the practical implication of the training. Only a very limited number of runners could have access to these equipment, therefore it is important for future research to develop sensors that could be used for in-field gait retraining which will be further discussed in section 7.7.

4) Being the first study to evaluate a gait retraining which promotes MFS landing in runners using real-time footstrike information, the main study in Chapter 4-5 was designed to be preliminary in nature. We did not conduct long-term follow-up (>1 month) on the biomechanics and injury occurrence in the trained runners, and also we did not include a control group. However, with the inconsistent effect on impact loading after the training, adjustments to the current training protocol would be required before conducting a similar study in larger scale and examine the clinical outcome. Data on injury occurrence would only be relevant when the training protocol was found effective in promoting favourable running biomechanics in a wider range of runners.

7.6 Practical implication and clinical significance

The RCT presented in Chapter 3 has provided evidence to support the use of visual feedback in lowering the impact loading, and gait retraining was considered a safe and effective intervention to prevent RRIs. The high prevalence of RRIs among the growing running population has been a global concern. The detrimental effects have not only affected the pleasure and performance of runners, but the healthcare utilization cost for treating an RRI could also place an economic burden on the runner and stress on the healthcare system. Intervention that could reduce the risk is particularly crucial for people to enjoy the physical exercise and its potential health benefits.

The study in Chapter 3 is also important for it displayed the effectiveness of modifying gait, favourable running mechanics does not equate to injury-free running. A difference in injury pattern has been observed among the trained runners. Therefore, prescription of gait retraining to runners at-risk should also consider the potential of incurring other types of injuries.

Chapter 4 and 5 provided a comprehensive evaluation of a visual-feedback gait retraining which promotes MFS landing. Based on scientific evidence, some researchers have proposed a switch from RFS to MFS would reduce impact loading, and subsequently reduce the risk of injury (Altman and Davis, 2009). Such notion has been much disputed, mainly due to the lack of conclusive evidence in support of a footstrike pattern switch, especially MFS (Hamill and Gruber, 2017). Chapter 4 and 5 have demonstrated, from the findings, that the footstrike pattern switch could be beneficial to some, but not all runners. Underlying factors including joint stiffness were proposed to be a determinant, and warrant further investigation.

Results in chapter 5 suggested that the change in FSA could be sustained after one month and also transferred to the untrained limb. This finding is of practical significance, especially for study that aimed to reduce the risk of RRIs. The effect of the training has to last, for most RRI are overuse injuries, and an intervention is only meaningful if runners were able to maintain the modified gait after the training. As RRI could affect either side of the human body, if runners were to reduce their risk on one side, or even compensate through the other, the significance of such an intervention would be greatly compromised.

Chapter 6 presented the effect of cushioning and comfort on running biomechanics. Runners' belief and the intuition of cushioning in their footwear has the potential to increase their impact force during running (Robbins and Waked, 1997), and causing detrimental effect. Subjectively, runners considered footwear as one of the main extrinsic factor that could prevent or induce injuries (Saragiotto et al., 2014). The study on MAX provides scientific evidence that was not in support of using this type of footwear as means of protection against impact during running. Another study in Chapter 6 has examined the effect of deceptive messages and price cue on runners' perception of comfort, and whether comfort alone would alter running biomechanics.

7.7 Future research directions

The RCT described in Chapter 3 was conducted on a group of novice runners, who are easier to change as compared to experienced runner who have made years of practice and could be harder to modify.

The main study in Chapter 4 and 5 was to explore the effectiveness in using a type of feedback that could be provided to runners in their natural running environment, the footstrike pattern. Recently, a novel footstrike pattern detection method has been introduced (Cheung et al., 2017). This method made use of force sensors placed under the insole at the heel and forefoot region of the running shoes and using the onset time difference between the sensors to predict the footstrike pattern of each step. Previously, footstrike detection would either require force plates or motion caption systems, which limits its application for the general public. This simple method provided an alternative, and has the potential to be developed into wireless real-time footstrike feedback device for runners to train in-field.

Recent technological advances in wearable sensors has created the possibility to conduct gait retraining in-field (Napier et al., 2017; Shull et al., 2014), and we have evidence to support the effectiveness in lowering impact (Willy et al., 2016). However, a comparison between lab-based and in-field gait retraining has yet been investigated. The training protocols adopted nowadays were established for a lab-based gait retraining in a controlled environment. A modification to the existing protocol, such as to consider external factors and scenarios in the outdoor environment, is therefore warranted. There has been studies which has started addressing these concerns, including the distraction outdoors (Cheung et al., 2018) and the use of a more practical type of feedback i.e. audio (Wood and Kipp, 2014), and more research effort should be put towards this so as to overcome the challenge in taking the gait retraining into the natural training environments.

The investigation on footwear properties in Chapter 6 has demonstrated the potential of footwear in altering runners’ perception of comfort, running kinetics and kinematics. The immediate changes we found in the running mechanics when runners switch into a new type of footwear with extreme cushioning could be compared with those who habitually run in this type of footwear, or further studies with a longer follow-up on a footwear transition programme could provide an even more comprehensive evaluation on the design, and prompt necessary modification.

7.8 Conclusion

This thesis provides evidence to support gait retraining in preventing running injuries, laying a foundation for the clinical significance and application of gait retraining. In addition, a gait retraining which promotes MFS landing has been evaluated based on impact reduction, sustainability and inter-limb motor skill transfer of the modified gait pattern. Trained runners were able to modify their gait to a certain extent, and such modification could be sustained after a month and transferred to the untrained side as well. However, the changes in impact loading was not consistent among runners, and suggest further examination on the modulation of joint stiffness. Footwear cushioning might be able to alter runners' biomechanics, but the effect was found to vary between running environment and the natural footstrike pattern of the runners.

APPENDIX I

Monthly online survey for running-related injuries

減低著地負荷速率對預防初學跑手之受傷 (每月問卷)

Gait retraining for the Reduction of Injury Occurrence in Novice Runners (Monthly survey)

* Required

1. **四位數字跑手編號 Runner ID** *
   從提示電郵內可找到你的跑手編號 Your runner ID is shown on the monthly reminder email

上月跑步資料

Running log of the past month

2. **上月跑步總里數 (公里)** *
   Total mileage in the past month (km)

3. **平均每週跑步里數 (公里)** *
   Average weekly mileage in the past month (km)

4. **每週跑步次數** *
   Average number of runs per week in the past month

5. **每次跑步平均花多長時間 (分鐘)** *
   Average duration of each run (min)

6. **平均跑步訓練速度 (分鐘 / 公里, 例: 5分30秒跑 1km，請填寫 5.5)** *
   Average training speed (min/km)

跑步受傷記錄

Running injury record

7. **你上一個月有沒有跑步引致之傷患?** *
   Were you affected by any running-related injury in the past month?
   Mark only one oval.

   ○ 有 (Yes) **Skip to question 8.**
   ○ 沒有 (No) **Stop filling out this form.**

跑步受傷 Running Injury

8. **請指出傷患: The injury:** *

Mark only one oval.

○ 脛前疼痛 (Shin splints)
○ 足底筋膜炎 (Plantar fasciitis)
○ 髕腱炎 (Patellar tendinitis)
○ 阿基里斯肌腱炎 (Achilles tendinitis)
○ 小腿後肌拉傷 (Calf strain)
○ 髕股關節痛 (Patellofemoral pain)
○ 半月板損傷 (Meniscal injury)
○ 髂脛束綜合症 (Iliotibial band syndrome)
○ 大腿後肌拉傷 (Hamstrings strain)
○ 下腰痛 (Low back pain)
○ 坐骨神經痛 (Sciatica)
○ 背肌拉傷 (Pulled back muscle)
○ 直接撞傷背部 (Direct contusion of the back)
○ 腹股溝拉傷 (Groin strain)
○ 腹股溝疝 (Inguinal hernia)
○ 髖部肌肉拉傷 (Hip muscle strain)
○ 髖部關節滑囊炎 (Hip joint bursitis)
○ 梨狀肌綜合症 (Piriformis syndrome)
○ 髖部骨折 (Hip fracture)
○ 膝部滑囊炎 (Knee bursitis)
○ 髕骨半脫位/脫位 (Patella subluxation / dislocation)
○ 膝部骨折 (Knee fracture)
○ 韌帶撕裂(如前十字韌帶/ 後十字韌帶/ 內側韌帶/ 外側韌帶) (Torn ligaments (e.g. ACL/PCL/MCL/LCL))
○ 大腿骨折 (Thigh fracture)
○ 骨筋膜室綜合症 (Compartment syndrome)
○ 小腿骨折 (Lower leg fracture)
○ 腳踝肌腱炎 (Ankle tendinitis)
○ 足踝扭傷 (Ankle sprain)
○ 腳踝滑囊炎 (Ankle bursitis)
○ 腳踝骨折 (Ankle fracture)
○ 骰狀骨綜合症 (Cuboid syndrome)
○ 莫通氏神經瘤 (Morton’s neuroma)
○ 腳部骨折 (Foot fracture)
○ Other: ____________________

9. **請指出傷患側** *

Which side were you injured?
Mark only one oval.

○ 左 (Left)
○ 右 (Right)
○ 左右同時受傷 (Both)

10. **請指出受傷日期** *

When were you injured?

____
Example: December 15, 2012

11. **你因傷患停止了幾多天跑步訓練? (天)** *

How many days of training did you miss because of this injury? (day)

____

12. **此傷患需要入院治療嗎?** *

Were you admitted to a hospital because of this injury?
Mark only one oval.

○ 需要 (Yes)
○ 不需要 (No)

13. **此傷患需要接受手術嗎?** *

Did you go through surgery for this injury?
Mark only one oval.

○ 需要 (Yes)
○ 不需要 (No)

14. **此傷患需要物理治療或其他康復治療嗎?** *

Did you go through physical therapy or other rehabilitation treatments for this injury?
Mark only one oval.

○ 需要 (Yes)
○ 不需要 (No)

15. **請選出此傷患的檢查或診斷程序** *

Please select the examination(s) that you went through during the diagnosis of this injury:
Check all that apply.

□ X光 (X-Ray)
□ 磁力共振 (MRI)
□ 骨骼掃描 (Bone scan)
□ 骨筋膜室綜合症測試 (Compartment test)
□ 醫護人員進行的身體檢查 (Physical examination by medial professional)
□ 沒有進行任何檢查或診斷程序 (None)
□ Other: ______________________

16. **此傷患經由以下醫護或專業人員診斷** *

Who made the diagnosis of this injury ?

Check all that apply.

- □ 醫生 (Medical doctor)
- □ 物理治療師 (Physiotherapist)
- □ 跌打醫師 (Bone setter)
- □ 教練 (Coach)
- □ 沒有任何專業人員確診 (The injury was not diagnosed)
- □ Other: ____________________

17. **此傷患需接受以下醫護或專業人員處理** *

Who treated this injury?

Check all that apply.

- □ 醫生 (Medical doctor)
- □ 物理治療師 (Physiotherapist)
- □ 跌打醫師 (Bone setter)
- □ 教練 (Coach)
- □ 沒有任何專業人員確診 (The injury was not treated)
- □ Other: ____________________

18. **你是在什麼情況下受傷?** *

How were you injured?

Mark only one oval.

- ○ 跑步訓練 (Running training)
- ○ 跑步比賽 (Running competition)
- ○ 其他運動 (Sports other than running)
- ○ Other: ____________________

19. **你對於這一次受傷有沒有其他補充資料?**

Any additional information regarding this injury?

____

____

____

____

____

其他跑步引致之傷患

Other running-related injuries in the past month

20. **你上一個月有沒有其他跑步引致之傷患?** *

Were you affected by any other running-related injuries in the past month apart from this injury?

Mark only one oval.

- ○ 有 (Yes) **Skip to "***我們將會聯絡你並人手記錄有關你另一項受傷的資料，謝謝！***."**
- ○ 沒有 (No) **Skip to "***我們的實驗人員將會聯絡你以確認你所提供的資料，謝謝！***."**

我們的實驗人員將會聯絡你以確認你所提供的資料，謝謝！

Our research personnel will contact you to verify the information you provided.

我們將會聯絡你並人手記錄有關你另一項受傷的資料，謝謝！

Our research personnel will contact you to record the details of your other injury.

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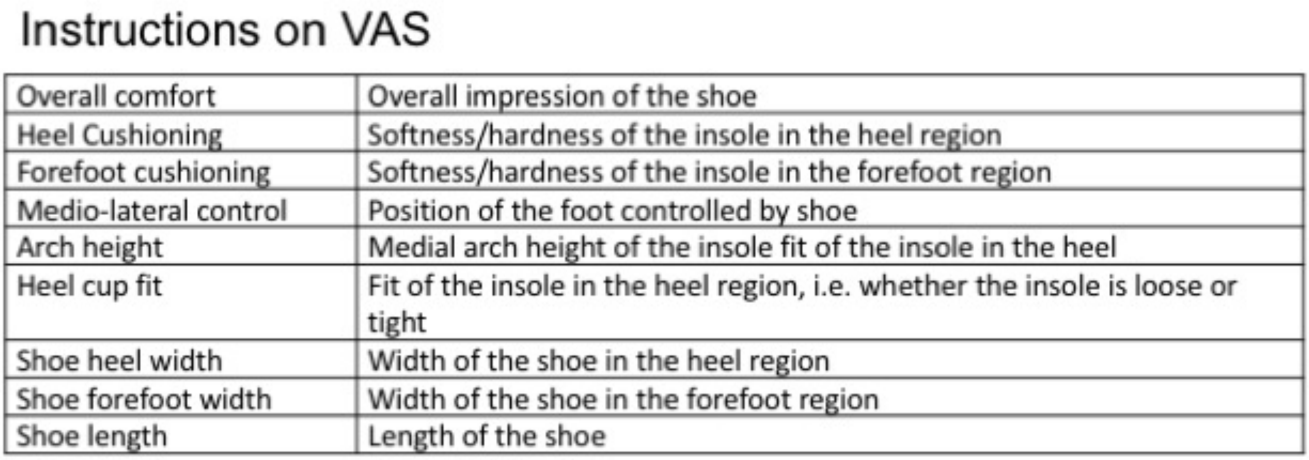
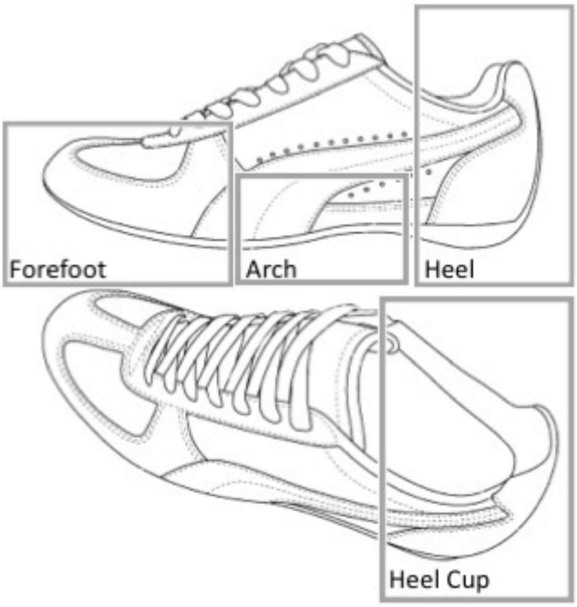
APPENDIX II

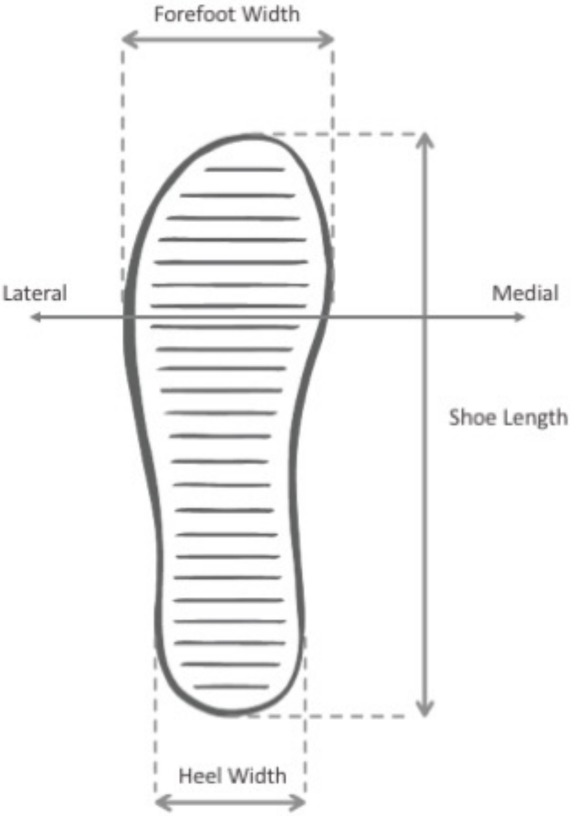
Information sheet on rating footwear comfort



Instructions on VAS

Overall comfort	Overall impression of the shoe
Heel Cushioning	Softness/hardness of the insole in the heel region
Forefoot cushioning	Softness/hardness of the insole in the forefoot region
Medio-lateral control	Position of the foot controlled by shoe
Arch height	Medial arch height of the insole fit of the insole in the heel
Heel cup fit	Fit of the insole in the heel region, i.e. whether the insole is loose or tight
Shoe heel width	Width of the shoe in the heel region
Shoe forefoot width	Width of the shoe in the forefoot region
Shoe length	Length of the shoe





APPENDIX III

Publications arising from the thesis

Articles published in peer-reviewed journals:

Chan, Z.Y.S., Au, I.P.H., Lau, F.O.Y., Ching, E.C.K., Zhang, J.H., Cheung, R.T.H., 2018. Does maximalist footwear lower impact loading during level ground and downhill running? European Journal of Sport Science 1–7

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H., An, W.W., Shum, G.L.K., Ng, G.Y.F., Cheung, R.T.H., 2017. Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial. The American Journal of Sports Medicine 036354651773627. https://doi.org/10.1177/0363546517736277

Conference presentations:

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, Pun, G.T.K., An, W.W., Cheung, R.T.H., 2017. Gait retraining reduces impact loading and injury risk in novice runners. The XXVI Congress of the International Society of Biomechanics (ISB 2017), 23 - 27 July 2017, Brisbane, Australia.

Cheung, R.T.H., Lau, F.O.Y., Ching, E.C.K., Chan, Z.Y.S., Zhang, J.H., Au, I.P.H., 2017. Maximalist shoes do not reduce impact loading during level and downhill running. Medicine & Science in Sports & Exercise. 49(5S):132. American College of Sports Medicine 64th Annual Meeting, 30 May - 3 June 2017, Denver, Colorado USA.

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, An, W.W., Cheung, R.T.H., 2017. Effects of deceptive footwear condition on subjective comfort and joint kinematics in runners. The 5th HKASMSS Student Conference, 26 November 2016, Hong Kong.

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, An, W.W., Cheung, R.T.H., 2017. Effects of a visual-feedback gait retraining on landing pattern transition in rear-foot strike runners. The 5th HKASMSS Student Conference, 26 November 2016, Hong Kong.

Conference abstracts accepted for presentation:

Chan Z.Y.S., Zhang J.H., Cheung R.T.H. (2018) Gait Retraining to Promote Mid-foot Landing in Habitual Rear-foot Landing Runners. 11th Pan Pacific Conference on Rehabilitation, 17-18 November, 2018, Hong Kong.

Chan Z.Y.S., Lau F.O.Y., Ching E.C.K., Zhang J.H., Au I.P.H., Cheung R.T.H. (2018) Enhanced Shoe Cushioning: Are they More Comfortable and Better in Impact Attenuation during Level and Downhill Running? 11th Pan Pacific Conference on Rehabilitation, 17-18 November, 2018, Hong Kong.

Chan Z.Y.S., Zhang J.H., Au I.P.H., An W.W., Cheung R.T.H. (2018) Biased Perception of Footwear Comfort in Runners: a Deceptive Cross-over study. 11th Pan Pacific Conference on Rehabilitation, 17-18 November, 2018, Hong Kong.

APPENDIX IV

Other publications during MPhil candidature

Journal articles:

Mangubat A.L.S., Zhang J.H., Chan Z.Y.S., MacPhail A.J.C, Au I.P.H., Cheung R.T.H., 2018. Biomechanical outcomes due to impact loading in runners while looking sideways. Journal of Applied Biomechanics 0, 1–14. https://doi.org/10.1123/jab.2017-0381

Cheung, R.T.H., An, W.W., Au, I.P.H., Zhang, J.H., Chan, Z.Y.S., MacPhail, A.J., 2018. Control of impact loading during distracted running before and after gait retraining in runners. Journal of Sports Sciences 36, 1497–1501. https://doi.org/10.1080/02640414.2017.1398886

Cheung, R.T.H., An, W.W., Au, I.P.H., Zhang, J.H., Chan, Z.Y.S., Man, A., Lau, F.O.Y., Lam, M.K.Y., Lau, K.K., Leung, C.Y., Tsang, N.W., Sze, L.K.Y., Lam, G.W.K., 2017. Measurement agreement between a newly developed sensing insole and traditional laboratory-based method for footstrike pattern detection in runners. PLoS ONE 12, e0175724. https://doi.org/10.1371/journal.pone.0175724

MacPhail, A.J.C., Au, I.P.H., Chan, M., Mak, D.N.T., An, W.W., Chan, Z.Y.S., Zhang, J.H., Wong, K., So, A., Chan, N., Kwok, C., Lau, P., Draper, D., Cheung, R.T.H., 2017. Type effect of inhibitory KT tape on measured vs. perceived maximal grip strength. Journal of Bodywork and Movement Therapies 0. https://doi.org/10.1016/j.jbmt.2017.10.011

Mak, D.N.T., Au, I.P.H., Chan, M., Chan, Z.Y.S., An, W.W., Zhang, J.H., Draper, D., Cheung, R.T.-H., 2018. Placebo effect of facilitatory Kinesio tape on muscle activity and muscle strength. Physiotherapy Theory and Practice 1–6. https://doi.org/10.1080/09593985.2018.1441936

Conference presentations:

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H, An, W.W., Cheung, R.T.H., 2018. A Prospective Study on Running-Related Injuries in Asian Runners. The 10th Annual Meeting of Japanese Orthopedic Society of Knee, Arthroscopy and Sports Medicine, 14-16 June 2018, Fukuoka, Japan.

Au, I.P.H, Lam, G.W.K., Chan, Z.Y.S., Zhang, J.H., Cheung, R.T.H., 2018. Effects of midsole thickness on running biomechanics. The 10th Annual Meeting of Japanese Orthopedic Society of Knee, Arthroscopy and Sports Medicine, 14-16 June 2018, Fukuoka, Japan.

REFERENCE

2018 Standard Chartered Hong Kong Marathon - Marathon Race Handbook, 2018.

Agresta, C., Brown, A., 2015. Gait Retraining for Injured and Healthy Runners Using Augmented Feedback: A Systematic Literature Review. Journal of Orthopaedic & Sports Physical Therapy 45, 576–584. https://doi.org/10.2519/jospt.2015.5823

Agresta, C., Kessler, S., Southern, E., Goulet, G.C., Zernicke, R., Zendler, J.D., 2018. Immediate and short-term adaptations to maximalist and minimalist running shoes. Footwear Science 1–13. https://doi.org/10.1080/19424280.2018.1460624

Ahn, A.N., Brayton, C., Bhatia, T., Martin, P., 2014. Muscle activity and kinematics of forefoot and rearfoot strike runners. Journal of Sport and Health Science 3, 102–112. https://doi.org/10.1016/j.jshs.2014.03.007

Altman, A.R., Davis, I.S., 2016. Prospective comparison of running injuries between shod and barefoot runners. British Journal of Sports Medicine 50, 476–480. https://doi.org/10.1136/bjsports-2014-094482

Altman, A.R., Davis, I.S., 2012. A kinematic method for footstrike pattern detection in barefoot and shod runners. Gait & Posture 35, 298–300. https://doi.org/10.1016/j.gaitpost.2011.09.104

Altman, A.R., Davis, I.S., 2009. Is midfoot striking during running advantageous over rearfoot or forefoot striking. State College (PA): American Society of Biomechanics.

An, W., Rainbow, M.J., Cheung, R.T.H., 2015. Effects of Surface Inclination on the Vertical Loading Rates and Landing Pattern during the First Attempt of Barefoot Running in Habitual Shod Runners. BioMed Research International 2015, 1–7. https://doi.org/10.1155/2015/240153

Archdeacon, M.T., Jepsen, K.J., Davy, D.T., 1996. The effects of torsional loading conditions and damage on bovine cortical bone strength. IEEE, pp. 445–448. https://doi.org/10.1109/SBEC.1996.493271

Arendse, R.E., Noakes, T.D., Azevedo, L.B., Romanov, N., Schwellnus, M.P., Fletcher, G., 2004. Reduced Eccentric Loading of the Knee with the Pose Running Method: Medicine & Science in Sports & Exercise 36, 272–277. https://doi.org/10.1249/01.MSS.0000113684.61351.B0

Baltich, J., Maurer, C., Nigg, B.M., 2015. Increased vertical impact forces and altered running mechanics with softer midsole shoes. PLoS ONE 10, e0125196. https://doi.org/10.1371/journal.pone.0125196

Barnes, R.A., Smith, P.D., 1994. The role of footwear in minimizing lower limb injury. Journal of Sports Sciences 12, 341–353. https://doi.org/10.1080/02640419408732180

Barrios, J.A., Crossley, K.M., Davis, I.S., 2010. Gait retraining to reduce the knee adduction moment through real-time visual feedback of dynamic knee alignment. Journal of Biomechanics 43, 2208–2213. https://doi.org/10.1016/j.jbiomech.2010.03.040

Barton, C.J., Bonanno, D.R., Carr, J., Neal, B.S., Malliaras, P., Franklyn-Miller, A., Menz, H.B., 2016. Running retraining to treat lower limb injuries: a mixed-methods study of current evidence synthesised with expert opinion. Br J Sports Med 50, 513–526. https://doi.org/10.1136/bjsports-2015-095278

Bishop, M., Fiolkowski, P., Conrad, B., Brunt, D., Horodyski, M., 2006. Athletic Footwear, Leg Stiffness, and Running Kinematics. J Athl Train 41, 387–392.

Blackmore, T., Willy, R.W., Creaby, M.W., 2016. The high frequency component of the vertical ground reaction force is a valid surrogate measure of the impact peak. Journal of Biomechanics 49, 479–483. https://doi.org/10.1016/j.jbiomech.2015.12.019

Booth, A.T.C., Buizer, A.I., Meyns, P., Oude Lansink, I.L.B., Steenbrink, F., van der Krogt, M.M., 2018. The efficacy of functional gait training in children and young adults with cerebral palsy: a systematic review and meta-analysis. Developmental Medicine & Child Neurology. https://doi.org/10.1111/dmcn.13708

Boston Marathon History: Participation [WWW Document], 2018. URL http://www.baa.org/races/boston-marathon/boston-marathon-history/participation.aspx (accessed 6.3.18).

Bovens, A., Janssen, G., Vermeer, H., Hoeberigs, J., Janssen, M., Verstappen, F., 1989. Occurrence of Running Injuries in Adults Following a Supervised Training Program. International Journal of Sports Medicine 10, S186–S190. https://doi.org/10.1055/s-2007-1024970

Boyer, E.R., Derrick, T.R., 2015. Select injury-related variables are affected by stride length and foot strike style during running. Am J Sports Med 43, 2310–2317. https://doi.org/10.1177/0363546515592837

Brazier, J., Bishop, C., Simons, C., Antrobus, M., Read, P.J., Turner, A.N., 2014. Lower extremity stiffness: Effects on performance and injury and implications for training. Strength & Conditioning Journal 36, 103–112.

Bredeweg, S.W., Zijlstra, S., Bessem, B., Buist, I., 2012. The effectiveness of a preconditioning programme on preventing running-related injuries in novice runners: a randomised controlled trial. Br J Sports Med 46, 865–870. https://doi.org/10.1136/bjsports-2012-091397

Breen, D.T., Foster, J., Falvey, E., Franklyn-Miller, A., 2015. Gair re-training to alleviate the symptoms of anterior exertional lower leg pain: a case series. Int J Sports Phys Ther 10, 85–94.

Butler, R.J., Crowell, H.P., Davis, I.M., 2003. Lower extremity stiffness: implications for performance and injury. Clin Biomech (Bristol, Avon) 18, 511–517.

Cavanagh, P.R., Lafortune, M.A., 1980. Ground reaction forces in distance running. Journal of Biomechanics 13, 397–406. https://doi.org/10.1016/0021-9290(80)90033-0

Chambon, N., Delattre, N., Guéguen, N., Berton, E., Rao, G., 2015. Shoe drop has opposite influence on running pattern when running overground or on a treadmill. Eur. J. Appl. Physiol. 115, 911–918. https://doi.org/10.1007/s00421-014-3072-x

Chambon, N., Delattre, N., Guéguen, N., Berton, E., Rao, G., 2014. Is midsole thickness a key parameter for the running pattern? Gait Posture 40, 58–63. https://doi.org/10.1016/j.gaitpost.2014.02.005

Chan, Z.Y.S., Zhang, J.H., Au, I.P.H., An, W.W., Shum, G.L.K., Ng, G.Y.F., Cheung, R.T.H., 2017. Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial. The American Journal of Sports Medicine 036354651773627. https://doi.org/10.1177/0363546517736277

Chen, T.L., An, W.W., Chan, Z.Y.S., Au, I.P.H., Zhang, Z.H., Cheung, R.T.H., 2016. Immediate effects of modified landing pattern on a probabilistic tibial stress fracture model in runners. Clinical Biomechanics 33, 49–54. https://doi.org/10.1016/j.clinbiomech.2016.02.013

Cheung, R.T.H., An, W.W., Au, I.P.H., Zhang, J.H., Chan, Z.Y.S., MacPhail, A.J., 2018. Control of impact loading during distracted running before and after gait retraining in runners. Journal of Sports Sciences 36, 1497–1501. https://doi.org/10.1080/02640414.2017.1398886

Cheung, R.T.H., An, W.W., Au, I.P.H., Zhang, J.H., Chan, Z.Y.S., Man, A., Lau, F.O.Y., Lam, M.K.Y., Lau, K.K., Leung, C.Y., Tsang, N.W., Sze, L.K.Y., Lam, G.W.K., 2017. Measurement agreement between a newly developed sensing insole and traditional laboratory-based method for footstrike pattern detection in runners. PLoS ONE 12, e0175724. https://doi.org/10.1371/journal.pone.0175724

Cheung, R.T.H., Davis, I.S., 2011. Landing Pattern Modification to Improve Patellofemoral Pain in Runners: A Case Series. Journal of Orthopaedic & Sports Physical Therapy 41, 914–919. https://doi.org/10.2519/jospt.2011.3771

Cheung, R.T.H., Ng, G.Y.F., 2007. Efficacy of motion control shoes for reducing excessive rearfoot motion in fatigued runners. Physical Therapy in Sport 8, 75–81. https://doi.org/10.1016/j.ptsp.2006.12.002

Cheung, R.T.H., Wong, R.Y.L., Chung, T.K.W., Choi, R.T., Leung, W.W.Y., Shek, D.H.Y., 2016a. Relationship between foot strike pattern, running speed, and footwear condition in recreational distance runners. Sports Biomechanics 0, 1–10. https://doi.org/10.1080/14763141.2016.1226381

Cheung, R.T.H., Wong, R.Y.L., Chung, T.K.W., Choi, R.T., Leung, W.W.Y., Shek, D.H.Y., 2016b. Relationship between foot strike pattern, running speed, and footwear condition in recreational distance runners. Sports Biomechanics 1–10. https://doi.org/10.1080/14763141.2016.1226381

Choi, J.T., Bastian, A.J., 2007. Adaptation reveals independent control networks for human walking. Nature Neuroscience 10, 1055–1062. https://doi.org/10.1038/nn1930

Clansey, A.C., Hanlon, M., Wallace, E.S., Nevill, A., Lake, M.J., 2014. Influence of tibial shock feedback training on impact loading and running economy. Med Sci Sports Exerc 46, 973–981. https://doi.org/10.1249/MSS.0000000000000182

Clarke, T.E., Frederick, E.C., Cooper, L.B., 1983. Effects of shoe cushioning upon ground reaction forces in running. Int J Sports Med 4, 247–251. https://doi.org/10.1055/s-2008-1026043

Clinghan, R., Arnold, G.P., Drew, T.S., Cochrane, L.A., Abboud, R.J., 2008. Do you get value for money when you buy an expensive pair of running shoes? British Journal of Sports Medicine 42, 189–193. https://doi.org/10.1136/bjsm.2007.038844

Cohen, J., 1988. Statistical power analysis for the behavioral sciences, 2nd ed. ed. L. Erlbaum Associates, Hillsdale, N.J.

Crenshaw, S.J., Richards, J.G., 2006. A method for analyzing joint symmetry and normalcy, with an application to analyzing gait. Gait Posture 24, 515–521. https://doi.org/10.1016/j.gaitpost.2005.12.002

Criscenti, G., De Maria, C., Sebastiani, E., Tei, M., Placella, G., Speziali, A., Vozzi, G., Cerulli, G., 2015. Quasi-linear viscoelastic properties of the human medial patello-femoral ligament. J Biomech 48, 4297–4302. https://doi.org/10.1016/j.jbiomech.2015.10.042

Crowell, H.P., Davis, I.S., 2011. Gait retraining to reduce lower extremity loading in runners. Clinical Biomechanics 26, 78–83. https://doi.org/10.1016/j.clinbiomech.2010.09.003

Crowell, H.P., Milner, C.E., Hamill, J., Davis, I.S., 2010. Reducing Impact Loading During Running With the Use of Real-Time Visual Feedback. Journal of Orthopaedic & Sports Physical Therapy 40, 206–213. https://doi.org/10.2519/jospt.2010.3166

Daoud, A.I., Geissler, G.J., Wang, F., Saretsky, J., Daoud, Y.A., Lieberman, D.E., 2012. Foot Strike and Injury Rates in Endurance Runners: A Retrospective Study. Medicine & Science in Sports & Exercise 44, 1325–1334. https://doi.org/10.1249/MSS.0b013e3182465115

Davis, I.S., Bowser, B.J., Mullineaux, D.R., 2016. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. Br J Sports Med 50, 887–892. https://doi.org/10.1136/bjsports-2015-094579

Davis, I.S., Futrell, E., 2016. Gait Retraining: Altering the Fingerprint of Gait. Physical Medicine and Rehabilitation Clinics of North America, Running Injuries 27, 339–355. https://doi.org/10.1016/j.pmr.2015.09.002

Delgado, T.L., Kubera-Shelton, E., Robb, R.R., Hickman, R., Wallmann, H.W., Dufek, J.S., 2013. Effects of Foot Strike on Low Back Posture, Shock Attenuation, and Comfort in Running: Medicine & Science in Sports & Exercise 45, 490–496. https://doi.org/10.1249/MSS.0b013e3182781b2c

Diebal, A.R., Gregory, R., Alitz, C., Gerber, J.P., 2012. Forefoot Running Improves Pain and Disability Associated With Chronic Exertional Compartment Syndrome. Am J Sports Med 40, 1060–1067. https://doi.org/10.1177/0363546512439182

Diebal, A.R., Gregory, R., Alitz, C., Gerber, J.P., 2011. Effects of forefoot running on chronic exertional compartment syndrome: A case series. ResearchGate 6, 312–21.

Dinato, R.C., Ribeiro, A.P., Butugan, M.K., Pereira, I.L.R., Onodera, A.N., Sacco, I.C.N., 2015. Biomechanical variables and perception of comfort in running shoes with different cushioning technologies. Journal of Science and Medicine in Sport 18, 93–97. https://doi.org/10.1016/j.jsams.2013.12.003

Divert, C., Baur, H., Mornieux, G., Mayer, F., Belli, A., 2005. Stiffness adaptations in shod running. J Appl Biomech 21, 311–321.

Dixon, S.J., 2008. Use of pressure insoles to compare in-shoe loading for modern running shoes. Ergonomics 51, 1503–1514. https://doi.org/10.1080/00140130802239562

Dixon, S.J., Collop, A.C., Batt, M.E., 2000. Surface effects on ground reaction forces and lower extremity kinematics in running. Medicine and Science in Sports and Exercise 32, 1919–1926.

Dommelen, J.A.W. van, Jolandan, M.M., Ivarsson, B.J., Millington, S.A., Raut, M., Kerrigan, J.R., Crandall, J.R., Diduch, D.R., 2005. Pedestrian Injuries: Viscoelastic Properties of Human Knee Ligaments at High Loading Rates. Traffic Injury Prevention 6, 278–287. https://doi.org/10.1080/15389580590969436

Dreyer, D., Dreyer, K., 2009. ChiRunning: a revolutionary approach to effortless, injury-free running. Simon & Schuster, New York.

Esculier, J.-F., Dubois, B., Dionne, C.E., Leblond, J., Roy, J.-S., 2015. A consensus definition and rating scale for minimalist shoes. Journal of Foot and Ankle Research 8. https://doi.org/10.1186/s13047-015-0094-5

Fellin, R.E., Manal, K., Davis, I.S., 2010. Comparison of lower extremity kinematic curves during overground and treadmill running. J Appl Biomech 26, 407–414.

Fong Yan, A., Sinclair, P.J., Hiller, C., Wegener, C., Smith, R.M., 2013. Impact attenuation during weight bearing activities in barefoot vs. shod conditions: A systematic review. Gait & Posture 38, 175–186. https://doi.org/10.1016/j.gaitpost.2012.11.017

Giandolini, M., Arnal, P.J., Millet, G.Y., Peyrot, N., Samozino, P., Dubois, B., Morin, J.-B., 2013. Impact reduction during running: efficiency of simple acute interventions in recreational runners. European Journal of Applied Physiology 113, 599–609. https://doi.org/10.1007/s00421-012-2465-y

Goss, D.L., Gross, M.T., 2012. Relationships among self-reported shoe type, footstrike pattern, and injury incidence. US Army Med Dep J 25–30.

Goss, D.L., Lewek, M., Yu, B., Ware, W.B., Teyhen, D.S., Gross, M.T., 2015. Lower Extremity Biomechanics and Self-Reported Foot-Strike Patterns Among Runners in Traditional and Minimalist Shoes. Journal of Athletic Training 50, 603–611. https://doi.org/10.4085/1062-6050.49.6.06

Gottschall, J.S., Kram, R., 2005. Ground reaction forces during downhill and uphill running. Journal of Biomechanics 38, 445–452. https://doi.org/10.1016/j.jbiomech.2004.04.023

Hamill, J., Gruber, A.H., 2017. Is changing footstrike pattern beneficial to runners? Journal of Sport and Health Science 6, 146–153. https://doi.org/10.1016/j.jshs.2017.02.004

Hamill, J., Gruber, A.H., Derrick, T.R., 2014. Lower extremity joint stiffness characteristics during running with different footfall patterns. Eur J Sport Sci 14, 130–136. https://doi.org/10.1080/17461391.2012.728249

Hamill, J., Moses, M., Seay, J., 2009. Lower extremity joint stiffness in runners with low back pain. Res Sports Med 17, 260–273. https://doi.org/10.1080/15438620903352057

Handsaker, J.C., Forrester, S.E., Folland, J.P., Black, M.I., Allen, S.J., 2016. A kinematic algorithm to identify gait events during running at different speeds and with different footstrike types. Journal of Biomechanics 49, 4128–4133. https://doi.org/10.1016/j.jbiomech.2016.10.013

Hasegawa, H., Yamauchi, T., Kraemer, W.J., 2007. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. The Journal of Strength & Conditioning Research 21, 888–893.

Hazell, L., Chockalingam, N., 2009. A preliminary study into the effect of running shoes on stride length. Footwear Science 1, 41–42. https://doi.org/10.1080/19424280902977186

Hennig, E.M., 2011. Eighteen years of running shoe testing in Germany – a series of biomechanical studies. Footwear Science 3, 71–81. https://doi.org/10.1080/19424280.2011.616536

Hennig, E.M., Milani, T.L., Lafortune, M.A., 1993. Use of Ground Reaction Force Parameters in Predicting Peak Tibial Accelerations in Running. Journal of Applied Biomechanics 9, 306–314. https://doi.org/10.1123/jab.9.4.306

Hennig, E.M., Schulz, J., 2011. Subjective evaluation of biomechanical shoe properties during blinded and non-blinded running. Footwear Science 3, S75–S76. https://doi.org/10.1080/19424280.2011.575802

Hespanhol Junior, L.C., van Mechelen, W., Postuma, E., Verhagen, E., 2016. Health and economic burden of running-related injuries in runners training for an event: A prospective cohort study. Scand J Med Sci Sports 26, 1091–1099. https://doi.org/10.1111/sms.12541

Horvais, N., Samozino, P., 2013. Effect of midsole geometry on foot-strike pattern and running kinematics. Footwear Science 5, 81–89. https://doi.org/10.1080/19424280.2013.767863

Hreljac, A., 2005. Etiology, Prevention, and Early Intervention of Overuse Injuries in Runners: a Biomechanical Perspective. Physical Medicine and Rehabilitation Clinics of North America, Running Injuries 16, 651–667. https://doi.org/10.1016/j.pmr.2005.02.002

Hreljac, A., Marshall, R.N., Hume, P.A., 2000. Evaluation of lower extremity overuse injury potential in runners. Med Sci Sports Exerc 32, 1635–1641.

Hulteen, R.M., Smith, J.J., Morgan, P.J., Barnett, L.M., Hallal, P.C., Colyvas, K., Lubans, D.R., 2017. Global participation in sport and leisure-time physical activities: A systematic review and meta-analysis. Preventive Medicine 95, 14–25. https://doi.org/10.1016/j.ypmed.2016.11.027

Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., Gainey, J., Gorton, G., Cochran, G.V., 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J. Orthop. Res. 7, 849–860. https://doi.org/10.1002/jor.1100070611

Keller, T.S., Weisberger, A.M., Ray, J.L., Hasan, S.S., Shiavi, R.G., Spengler, D.M., 1996. Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. Clinical Biomechanics 11, 253–259. https://doi.org/10.1016/0268-0033(95)00068-2

Kemper, A.R., McNally, C., Manoogian, S.J., Duma, S.M., 2008. Tensile material properties of human tibia cortical bone effects of orientation and loading rate. Biomed Sci Instrum 44, 419–427.

Kluitenberg, B., Middelkoop, M. van, Diercks, R., Worp, H. van der, 2015. What are the Differences in Injury Proportions Between Different Populations of Runners? A Systematic Review and Meta-Analysis. Sports Med 45, 1143–1161. https://doi.org/10.1007/s40279-015-0331-x

Knobloch, K., Yoon, U., Vogt, P.M., 2008. Acute and overuse injuries correlated to hours of training in master running athletes. Foot Ankle Int 29, 671–676. https://doi.org/10.3113/FAI.2008.0671

Kong, P.W., Candelaria, N.G., Smith, D.R., 2009. Running in new and worn shoes: a comparison of three types of cushioning footwear. Br J Sports Med 43, 745–749. https://doi.org/10.1136/bjsm.2008.047761

Krishnan, C., Ranganathan, R., Tetarbe, M., 2017. Interlimb transfer of motor skill learning during walking: No evidence for asymmetric transfer. Gait & Posture 56, 24–30. https://doi.org/10.1016/j.gaitpost.2017.04.032

Kuitunen, S., Komi, P.V., Kyröläinen, H., 2002. Knee and ankle joint stiffness in sprint running. Med Sci Sports Exerc 34, 166–173.

Kulmala, J.-P., Avela, J., Pasanen, K., Parkkari, J., 2013. Forefoot Strikers Exhibit Lower Running-Induced Knee Loading than Rearfoot Strikers: Medicine & Science in Sports & Exercise 45, 2306–2313. https://doi.org/10.1249/MSS.0b013e31829efcf7

Lafortune, M.A., Lake, M.J., 1995. Human pendulum approach to simulate and quantify locomotor impact loading. Journal of Biomechanics 28, 1111–1114. https://doi.org/10.1016/0021-9290(95)00002-Y

Larson, P., Higgins, E., Kaminski, J., Decker, T., Preble, J., Lyons, D., McIntyre, K., Normile, A., 2011. Foot strike patterns of recreational and sub-elite runners in a long-distance road race. J Sports Sci 29, 1665–1673. https://doi.org/10.1080/02640414.2011.610347

Laughton, C.A., Davis, I.M., Hamill, J., 2003. Effect of Strike Pattern and Orthotic Intervention on Tibial Shock during Running. Journal of Applied Biomechanics 19, 153–168. https://doi.org/10.1123/jab.19.2.153

Lieberman, D.E., Venkadesan, M., Werbel, W.A., Daoud, A.I., D'Andrea, S., Davis, I.S., Mang'Eni, R.O., Pitsiladis, Y., 2010. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 463, 531–535. https://doi.org/10.1038/nature08723

Liebermann, D.G., Katz, L., Hughes, M.D., Bartlett, R.M., McClements, J., Franks, I.M., 2002. Advances in the application of information technology to sport performance. Journal of Sports Sciences 20, 755–769. https://doi.org/10.1080/026404102320675611

Logan, S., Hunter, I., J Ty Hopkins, J.T., Feland, J.B., Parcell, A.C., 2010. Ground reaction force differences between running shoes, racing flats, and distance spikes in runners. J Sports Sci Med 9, 147–153.

Lun, V., Meeuwisse, W.H., Stergiou, P., Stefanyshyn, D., 2004. Relation between running injury and static lower limb alignment in recreational runners. Br J Sports Med 38, 576–580. https://doi.org/10.1136/bjsm.2003.005488

Mauroy, G., Schepens, B., Willems, P.A., 2014. Leg stiffness and joint stiffness while running to and jumping over an obstacle. Journal of Biomechanics 47, 526–535. https://doi.org/10.1016/j.jbiomech.2013.10.039

McMahon, T.A., Cheng, G.C., 1990. The mechanics of running: How does stiffness couple with speed? Journal of Biomechanics, International Society of Biomechanics 23, 65–78. https://doi.org/10.1016/0021-9290(90)90042-2

McNair, P.J., Marshall, R.N., 1994. Kinematic and kinetic parameters associated with running in different shoes. Br J Sports Med 28, 256–260. https://doi.org/10.1136/bjsm.28.4.256

Mercer, J., Vance, J., Hreljac, A., Hamill, J., 2002. Relationship between shock attenuation and stride length during running at different velocities. European Journal of Applied Physiology 87, 403–408. https://doi.org/10.1007/s00421-002-0646-9

Messier, S.P., Cirillo, K.J., 1989. Effects of a verbal and visual feedback system on running technique, perceived exertion and running economy in female novice runners. J Sports Sci 7, 113–126. https://doi.org/10.1080/02640418908729830

Meyer, C., Mohr, M., Falbriard, M., Nigg, S.R., Nigg, B.M., 2018. Influence of footwear comfort on the variability of running kinematics. Footwear Science 10, 29–38. https://doi.org/10.1080/19424280.2017.1388296

Milani, T.L., Hennig, E.M., Lafortune, M.A., 1997. Perceptual and biomechanical variables for running in identical shoe constructions with varying midsole hardness. Clinical Biomechanics 12, 294–300. https://doi.org/10.1016/S0268-0033(97)00008-9

Miller, J.E., Nigg, B.M., Liu, W., Stefanyshyn, D.J., Nurse, M.A., 2000. Influence of Foot, Leg and Shoe Characteristics on Subjective Comfort. Foot & Ankle International 21, 759–767. https://doi.org/10.1177/107110070002100908

Mills, K., Blanch, P., Vicenzino, B., 2011. Influence of Contouring and Hardness of Foot Orthoses on Ratings of Perceived Comfort: Medicine & Science in Sports & Exercise 43, 1507–1512. https://doi.org/10.1249/MSS.0b013e31820e783f

Milner, C.E., Ferber, R., Pollard, C.D., Hamill, J., Davis, I.S., 2006. Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. Medicine &

Science in Sports & Exercise 38, 323–328. https://doi.org/10.1249/01.mss.0000183477.75808.92

Morris, T., Newby, N.A., Wininger, M., Craelius, W., 2009. Inter-limb transfer of learned ankle movements. Experimental Brain Research 192, 33–42. https://doi.org/10.1007/s00221-008-1547-x

Mündermann, A., Nigg, B.M., Stefanyshyn, D.J., Humble, R.N., 2002. Development of a reliable method to assess footwear comfort during running. Gait & Posture 16, 38–45. https://doi.org/10.1016/S0966-6362(01)00197-7

Mündermann, A., Stefanyshyn, D.J., Nigg, B.M., 2001. Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. Med Sci Sports Exerc 33, 1939–1945.

Napier, C., Esculier, J.-F., Hunt, M.A., 2017. Gait retraining: out of the lab and onto the streets with the benefit of wearables. British Journal of Sports Medicine 51, 1642–1643. https://doi.org/10.1136/bjsports-2017-098637

Nielsen, R.O., Buist, I., Sørensen, H., Lind, M., Rasmussen, S., 2012. Training errors and running related injuries: a systematic review. Int J Sports Phys Ther 7, 58–75.

Nigg, B.M., Bahlsen, H.A., Luethi, S.M., Stokes, S., 1987. The influence of running velocity and midsole hardness on external impact forces in heel-toe running. J Biomech 20, 951–959.

Noehren, B., Sanchez, Z., Cunningham, T., McKeon, P.O., 2012a. The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain. Gait & Posture 36, 596–599. https://doi.org/10.1016/j.gaitpost.2012.05.023

Noehren, B., Sanchez, Z., Cunningham, T., McKeon, P.O., 2012b. The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain. Gait Posture 36, 596–599. https://doi.org/10.1016/j.gaitpost.2012.05.023

Noehren, B., Scholz, J., Davis, I., 2011. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. Br J Sports Med 45, 691–696. https://doi.org/10.1136/bjsm.2009.069112

Nordin, A.D., Dufek, J.S., Mercer, J.A., 2017. Three-dimensional impact kinetics with foot-strike manipulations during running. Journal of Sport and Health Science 6, 489–497. https://doi.org/10.1016/j.jshs.2015.11.003

Novacheck, T.F., 1998. The biomechanics of running. Gait & Posture 7, 77–95. https://doi.org/10.1016/S0966-6362(97)00038-6

Nunnally, J.C., Bernstein, I.H., 1994. Psychometric theory, 3rd ed. ed, McGraw-Hill series in psychology. McGraw-Hill, New York.

Oja, P., Titze, S., Kokko, S., Kujala, U.M., Heinonen, A., Kelly, P., Koski, P., Foster, C., 2015. Health benefits of different sport disciplines for adults: systematic review of observational and intervention studies with meta-analysis. Br J Sports Med 49, 434–440. https://doi.org/10.1136/bjsports-2014-093885

Padulo, J., Annino, G., Migliaccio, G.M., D’Ottavio, S., Tihanyi, J., 2012. Kinematics of Running at Different Slopes and Speeds: Journal of Strength and Conditioning Research 26, 1331–1339. https://doi.org/10.1519/JSC.0b013e318231aafa

Petersen, M.K., Andersen, N.T., Mogensen, P., Voight, M., Søballe, K., 2011. Gait analysis after total hip replacement with hip resurfacing implant or Mallory-head Exeter prosthesis: a randomised controlled trial. Int Orthop 35, 667–674. https://doi.org/10.1007/s00264-010-1040-6

Pohl, M.B., Hamill, J., Davis, I.S., 2009. Biomechanical and Anatomic Factors Associated with a History of Plantar Fasciitis in Female Runners. Clinical Journal of Sport Medicine 19, 372–376. https://doi.org/10.1097/JSM.0b013e3181b8c270

Pohl, M.B., Mullineaux, D.R., Milner, C.E., Hamill, J., Davis, I.S., 2008. Biomechanical predictors of retrospective tibial stress fractures in runners. Journal of Biomechanics 41, 1160–1165. https://doi.org/10.1016/j.jbiomech.2008.02.001

Radin, E.L., Ehrlich, M.G., Chernack, R., Abernethy, P., Paul, I.L., Rose, R.M., 1978. Effect of Repetitive Impulsive Loading on the Knee Joints of Rabbits. Clinical Orthopaedics and Related Research® 288.

Reinschmidt, C., Nigg, B.M., 2000. Current issues in the design of running and court shoes. Sportverletz Sportschaden 14, 71–81.

Riley, P.O., Dicharry, J., Franz, J., Croce, U.D., Wilder, R.P., Kerrigan, D.C., 2008. A Kinematics and Kinetic Comparison of Overground and Treadmill Running: Medicine & Science in Sports & Exercise 40, 1093–1100. https://doi.org/10.1249/MSS.0b013e3181677530

Rixe, J.A., Gallo, R.A., Silvis, M.L., 2012. The barefoot debate: can minimalist shoes reduce running-related injuries? Curr Sports Med Rep 11, 160–165. https://doi.org/10.1249/JSR.0b013e31825640a6

Robbins, S., Waked, E., 1997. Hazard of deceptive advertising of athletic footwear. British Journal of Sports Medicine 31, 299–303. https://doi.org/10.1136/bjsm.31.4.299

Romanov, N., 2004. Dr. Nicholas Romanov's Pose Method of Running, 4.1.2004 edition. ed. Pose Method Publishing, Coral Gables, FL.

Romanov, N.S., Robson, J., 2004. Dr. Nicholas Romanov's Pose method of running: a new paradigm of running. PoseTech, Coral Gables, FL.

Rooney, B.D., Derrick, T.R., 2013. Joint contact loading in forefoot and rearfoot strike patterns during running. J Biomech 46, 2201–2206. https://doi.org/10.1016/j.jbiomech.2013.06.022

Roper, J.L., Harding, E.M., Doerfler, D., Dexter, J.G., Kravitz, L., Dufek, J.S., Mermier, C.M., 2016. The effects of gait retraining in runners with patellofemoral pain: A randomized trial. Clinical Biomechanics 35, 14–22. https://doi.org/10.1016/j.clinbiomech.2016.03.010

Ryan, M., Elashi, M., Newsham-West, R., Taunton, J., 2014. Examining injury risk and pain perception in runners using minimalist footwear. Br J Sports Med 48, 1257–1262. https://doi.org/10.1136/bjsports-2012-092061

Saragiotto, B.T., Yamato, T.P., Lopes, A.D., 2014. What Do Recreational Runners Think About Risk Factors for Running Injuries? A Descriptive Study of Their Beliefs and Opinions. Journal of Orthopaedic & Sports Physical Therapy 44, 733–738. https://doi.org/10.2519/jospt.2014.5710

Sasaki, N., 2012. Viscoelastic Properties of Biological Materials, in: De Vicente, J. (Ed.), Viscoelasticity - From Theory to Biological Applications. InTech. https://doi.org/10.5772/49979

Sawilowsky, S., 2009. New Effect Size Rules of Thumb. Journal of Modern Applied Statistical Methods 8. https://doi.org/10.22237/jmasm/1257035100

Schmidt, L., Skvortsova, V., Kullen, C., Weber, B., Plassmann, H., 2017. How context alters value: The brain's valuation and affective regulation system link price cues to experienced taste pleasantness. Scientific Reports 7. https://doi.org/10.1038/s41598-017-08080-0

Serink, R.T., Nachemson, A., Hansson, G., 1977. The Effect of Impact Loading on Rabbit Knee Joints. Acta Orthopaedica Scandinavica 48, 250–262. https://doi.org/10.3109/17453677708988764

Shea, C.H., Wulf, G., 1999. Enhancing motor learning through external-focus instructions and feedback. Human Movement Science 18, 553–571. https://doi.org/10.1016/S0167-9457(99)00031-7

Shih, Y., Lin, K.-L., Shiang, T.-Y., 2013. Is the foot striking pattern more important than barefoot or shod conditions in running? Gait & Posture 38, 490–494. https://doi.org/10.1016/j.gaitpost.2013.01.030

Shull, P.B., Jirattigalachote, W., Hunt, M.A., Cutkosky, M.R., Delp, S.L., 2014. Quantified self and human movement: a review on the clinical impact of wearable sensing and feedback for gait analysis and intervention. Gait Posture 40, 11–19. https://doi.org/10.1016/j.gaitpost.2014.03.189

Sigrist, R., Rauter, G., Riener, R., Wolf, P., 2013. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. Psychon Bull Rev 20, 21–53. https://doi.org/10.3758/s13423-012-0333-8

Sinclair, J., 2017. The influence of minimalist, maximalist and conventional footwear on impact shock attenuation during running. Movement & Sport Sciences - Science & Motricité 59–64. https://doi.org/10.1051/sm/2016010

Sinclair, J., 2014. Effects of barefoot and barefoot inspired footwear on knee and ankle loading during running. Clinical Biomechanics 29, 395–399. https://doi.org/10.1016/j.clinbiomech.2014.02.004

Sinclair, J., Fau-Goodwin, J., Richards, J., Shore, H., 2016. The influence of minimalist and maximalist footwear on the kinetics and kinematics of running. Footwear Science 8, 33–39. https://doi.org/10.1080/19424280.2016.1142003

Sinclair, J., Taylor, P.J., Hobbs, S.J., 2013. Digital Filtering of Three-Dimensional Lower Extremity Kinematics: an Assessment. J Hum Kinet 39, 25–36. https://doi.org/10.2478/hukin-2013-0065

Slater, K., 1985. Human comfort. C.C. Thomas, Springfield, Ill., U.S.A.

Snow, N.J., Blair, J.F.L., MacDonald, G.Z., Byrne, J.M., Basset, F.A., 2018. Barefoot running does not affect simple reaction time: an exploratory study. PeerJ 6. https://doi.org/10.7717/peerj.4605

Snyder, R., 1989. Misleading Characteristics of Implied-Superiority Claims. Journal of Advertising 18, 54–61. https://doi.org/10.1080/00913367.1989.10673167

Spiteri, T., Cochrane, J.L., Nimphius, S., 2013. The evaluation of a new lower-body reaction time test. J Strength Cond Res 27, 174–180. https://doi.org/10.1519/JSC.0b013e318250381f

Stanish, W.D., 1984. Overuse injuries in athletes: a perspective. Med Sci Sports Exerc 16, 1–7.

Stefanyshyn, D.J., Nigg, B.M., 1998. Dynamic Angular Stiffness of the Ankle Joint during Running and Sprinting. Journal of Applied Biomechanics 14, 292–299. https://doi.org/10.1123/jab.14.3.292

Stöckel, T., Wang, J., 2011. Transfer of short-term motor learning across the lower limbs as a function of task conception and practice order. Brain and Cognition 77, 271–279. https://doi.org/10.1016/j.bandc.2011.07.010

Tashman, S., Collon, D., Anderson, K., Kolowich, P., Anderst, W., 2004a. Abnormal Rotational Knee Motion During Running After Anterior Cruciate Ligament Reconstruction. Am J Sports Med 32, 975–983. https://doi.org/10.1177/0363546503261709

Tashman, S., Collon, D., Anderson, K., Kolowich, P., Anderst, W., 2004b. Abnormal Rotational Knee Motion during Running after Anterior Cruciate Ligament Reconstruction. The American Journal of Sports Medicine 32, 975–983. https://doi.org/10.1177/0363546503261709

Taunton, J., Ryan, M., Clement, D., McKenzie, D., Lloyd-Smith, D., Zumbo, B., 2002. A retrospective case-control analysis of 2002 running injuries. Br J Sports Med 36, 95–101. https://doi.org/10.1136/bjsm.36.2.95

Taylor, D.C., Dalton, J.D., Seaber, A.V., Garrett, W.E., 1990. Viscoelastic properties of muscle-tendon units: The biomechanical effects of stretching. The American Journal of Sports Medicine 18, 300–309. https://doi.org/10.1177/036354659001800314

Teasell, R.W., Bhogal, S.K., Foley, N.C., Speechley, M.R., 2003. Gait retraining post stroke. Top Stroke Rehabil 10, 34–65. https://doi.org/10.1310/UDXE-MJFF-53V2-EAP0

The HOKA® Difference | Technology by HOKA ONE ONE® [WWW Document], 2018. URL https://www.hokaoneone.com/technology.html (accessed 5.15.18).

Tschopp, M., Brunner, F., 2017. Diseases and overuse injuries of the lower extremities in long distance runners. Z Rheumatol 76, 443–450. https://doi.org/10.1007/s00393-017-0276-6

van der Worp, H., Vrielink, J.W., Bredeweg, S.W., 2016. Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. British Journal of Sports Medicine 50, 450–457. https://doi.org/10.1136/bjsports-2015-094924

van der Worp, M.P., ten Haaf, D.S.M., van Cingel, R., de Wijer, A., Nijhuis-van der Sanden, M.W.G., Staal, J.B., 2015. Injuries in Runners; A Systematic Review on Risk Factors and Sex Differences. PLoS One 10. https://doi.org/10.1371/journal.pone.0114937

van Gent, B.R.N., Siem, D.D., Middelkoop, M. van, Os, T.A.G. van, Bierma-Zeinstra, S.S.M.A., Koes, B.B.W., 2007. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. Br J Sports Med. https://doi.org/10.1136/bjsm.2006.033548

Van, H., Biedermann, M., Erni, T., Dietz, V., 2002. Obstacle avoidance during human walking: Transfer of motor skill from one leg to the other. Journal of Physiology 543, 709–717. https://doi.org/10.1113/jphysiol.2002.018473

Van Middelkoop, M., Kolkman, J., Van Ochten, J., Bierma-Zeinstra, S.M.A., Koes, B.W., 2008. Risk factors for lower extremity injuries among male marathon runners. Scand J Med Sci Sports 18, 691–697. https://doi.org/10.1111/j.1600-0838.2007.00768.x

van Poppel, D., Scholten-Peeters, G.G.M., van Middelkoop, M., Koes, B.W., Verhagen, A.P., 2018. Risk models for lower extremity injuries among short- and long distance runners: A prospective cohort study. Musculoskelet Sci Pract 36, 48–53. https://doi.org/10.1016/j.msksp.2018.04.007

Videbæk, S., Bueno, A.M., Nielsen, R.O., Rasmussen, S., 2015. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. Sports Med 45, 1017–1026. https://doi.org/10.1007/s40279-015-0333-8

Wen, D.Y., Puffer, J.C., Schmalzried, T.P., 1997. Lower extremity alignment and risk of overuse injuries in runners. Med Sci Sports Exerc 29, 1291–1298.

Williams, D.S., Davis, I.M., Scholz, J.P., Hamill, J., Buchanan, T.S., 2004. High-arched runners exhibit increased leg stiffness compared to low-arched runners. Gait & Posture 19, 263–269. https://doi.org/10.1016/S0966-6362(03)00087-0

Williams, D.S., McClay, I.S., Hamill, J., 2001. Arch structure and injury patterns in runners. Clin Biomech (Bristol, Avon) 16, 341–347.

Williams, D.S., McClay, I.S., Manal, K.T., 2000. Lower Extremity Mechanics in Runners with a Converted Forefoot Strike Pattern. Journal of Applied Biomechanics 16, 210–218. https://doi.org/10.1123/jab.16.2.210

Williams, P.T., 2009. Reduction in Incident Stroke Risk With Vigorous Physical Activity: Evidence From 7.7-Year Follow-Up of the National Runners' Health Study. Stroke 40, 1921–1923. https://doi.org/10.1161/STROKEAHA.108.535427

Willy, R.W., Buchenic, L., Rogacki, K., Ackerman, J., Schmidt, A., Willson, J.D., 2016. In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. Scand J Med Sci Sports 26, 197–205. https://doi.org/10.1111/sms.12413

Willy, R.W., Davis, I.S., 2014. Kinematic and Kinetic Comparison of Running in Standard and Minimalist Shoes: Medicine & Science in Sports & Exercise 46, 318–323. https://doi.org/10.1249/MSS.0b013e3182a595d2

Willy, R.W., Scholz, J.P., Davis, I.S., 2012. Mirror gait retraining for the treatment of patellofemoral pain in female runners. Clin Biomech (Bristol, Avon) 27, 1045–1051. https://doi.org/10.1016/j.clinbiomech.2012.07.011

Winstein, C.J., 1991. Knowledge of results and motor learning--implications for physical therapy. Phys Ther 71, 140–149.

Winter, D.A., 2009. Biomechanics and motor control of human movement, 4th ed. ed. Wiley, Hoboken, N.J.

Wood, C.M., Kipp, K., 2014. Use of audio biofeedback to reduce tibial impact accelerations during running. Journal of Biomechanics 47, 1739–1741. https://doi.org/10.1016/j.jbiomech.2014.03.008

Wulf, G., Shea, C., Lewthwaite, R., 2010. Motor skill learning and performance: a review of influential factors. Med Educ 44, 75–84. https://doi.org/10.1111/j.1365-2923.2009.03421.x

Wunsch, T., Kröll, J., Stöggl, T., Schwameder, H., 2016. Effects of a structured midsole on spatio-temporal variables and running economy in overground running. European Journal of Sport Science 0, 1–7. https://doi.org/10.1080/17461391.2016.1253776

Yong, J.R., Silder, A., Montgomery, K.L., Fredericson, M., Delp, S.L., 2018. Acute Changes in Foot Strike Pattern and Cadence Affect Running Parameters Associated with Tibial Stress Fractures. Journal of Biomechanics 0. https://doi.org/10.1016/j.jbiomech.2018.05.017

Zhang, J.H., An, W.W., Au, I.P.H., Chen, T.L., Cheung, R.T.H., 2016a. Comparison of the correlations between impact loading rates and peak accelerations measured at two different body sites: Intra- and inter-subject analysis. Gait & Posture 46, 53–56. https://doi.org/10.1016/j.gaitpost.2016.02.002

Zhang, J.H., McPhail, A.J.C., An, W.W., Naqvi, W.M., Chan, D.L.H., Au, I.P.H., Luk, A.T.W., Chen, T.L., Cheung, R.T.H., 2016b. A new footwear technology to promote non-heelstrike landing and enhance running performance: Fact or fad? Journal of Sports Sciences 1–5. https://doi.org/10.1080/02640414.2016.1224915