KINETICS CONTROL IN RUNNERS IN NATURAL-RUNNING CONDITIONS AFTER COMPLETION OF A LABORATORY-BASED GAIT RETRAINING PROGRAM

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Kinetics Control in Runners in Natural-running Conditions after Completion of A Laboratory-based Gait Retraining Program

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CERTIFICATE OF ORIGINALITY

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ZHANG HANWEN

ABSTRACT

This thesis consists of two sections. The main research question of the first section is how runners would maintain and translate a newly learned running gait into varied running conditions after completion of an established running gait retraining protocol. Instructed to soften their footfalls during training using real time biofeedback, runners were shown to effectively lower impact loading after completion of the training protocol. However, whether runners would be able to maintain the modified running biomechanics in other conditions was unclear. We conducted the first study in this section to establish an association between peak tibial shock and vertical loading rate, which was considered as a risk factor for running injuries. Based on this association, peak tibial shock could be used as a substitute of vertical loading rates in our further tests. The motor learning translation was then assessed in the second and third study in this section. The translation conditions included 1) inter-limb translation; 2) inter-speed translation; 3) inter-slope translation; and 4) treadmill-overground translation. Furthermore, we conducted a fourth study which aimed to assess the motor strategies adopted by the runners after the gait retraining program. This study aimed to address the question about how the motor strategies would affect the translation of learning effect.

The second section of this thesis included several exploratory studies that sought to explore applications of new technologies in gait modification, or to provide insights for future studies in the area of running biomechanics. The first study in the second section assessed a new shoe design and its effect in running gait. The second study in this section aimed to explore potential innate running biomechanics that might contribute to a better distance running performance. The third tried to apply an artificial neural network in the construction of a model to predict footstrike angle, which is a commonly used

kinematic parameter in running research. The fourth study described a wearable exoskeleton robot and reported some preliminary findings of the application of this robot in the area of stroke rehabilitation.

PUBLICATIONS ARISING FROM THE THESIS (Appendix II)

Articles published in peer-reviewed journals

1. **Zhang JH**, Chan ZYS, Au IPH, An WW, Shull PB, Cheung RTH. (2019) Transfer learning effects of biofeedback running retraining in untrained conditions. *Medicine & Science in Sports & Exercise*, DOI:10.1249/MSS.0000000000002007
2. **Zhang JH**, Chan ZYS, Au IPH, An WW, Cheung RTH. (2019) Can runners maintain the newly learned gait pattern outside laboratory environment following gait retraining? *Gait & Posture*, 69: 8-11
3. **Zhang JH**, McPhail AJC, An WW, Naqvi WM, Chan DLH, Au IPH, Luk ATW, Chen TLW, Cheung RTH. (2016) A new footwear technology to promote non-heelstrike landing and enhance running performance: Fact or fad? *Journal of Sports Sciences*, 35,15:1-5
4. **Zhang JH**, An WW, Au IPH, Chen TL, Cheung RTH. (2016) 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

Articles in preparation

1. **Zhang JH**, Chan ZYS, Cheung RTH (2019) African runners at two performance levels presented higher vertical stiffness and lower footstrike angle. *Scientific Reports*
2. **Zhang JH**, Chan ZYS, Cheung RTH. (2019) Kinetic and kinematic analysis of the learning effect of a laboratory-based gait retraining in untrained running conditions. *Journal of Science and Medicine in Sport*

3. **Zhang JH**, Jia YW, Chan ZYS, An WW, Au IPH, Xu Z, Cheung RTH (2019) An artificial neural network model to predict footstrike angle during varied runnings slopes. *PlosOne*

Conference proceedings:

1. **Zhang JH**, Kowk GHJ, Koh HY, Chan ZYS, Kwan KYH, Yip J, Cheung RTH. (2019) Gait differences between patients with adult degenerative scoliosis and healthy counterparts, The 10th Annual Meeting of Japanese Orthopaedic Society of Knee, Arthroscopy and Sports Medicine, 13-15 June, Sapporo, Japan
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4. **Zhang JH**, Chan ZYS, Au IPH, Lau FOY, An WW, Cheung RTH. (2018) A case study to identify potential innate biomechanical parameters in African distance runners: Comparison with Asian runners at different performance levels, 11th Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Poster Presentation Award)**
5. **Zhang JH**, Kowk G, Koh HY, Chan ZYS, Kwan K, Yip J, Cheung RTH. (2018) Gait differences between patients with adult degenerative scoliosis and health controls, 11th Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Poster Presentation Award)**

6. **Zhang JH**, Zoe Y.S. Chan, Ivan P.H. Au, Winko W. An, Roy T.H. Cheung. (2018) Can the Newly Learnt Gait Pattern after Running Retraining be Translated to Untrained Conditions? : 1547 Board# 8 May 31, 2018, American Colleague of Sports Medicine (ACSM) Annual Meeting
7. **Zhang JH**, Ho KY, Li KK, Li KM, Mark YP, Wu HM, Sin ELL, Chan ZYS, Au IPH, An WW, Cheung RTH (2017) A highly feasible exercise program to promote executive functions in young adults. International Symposium on Physical Activity & Fitness of the Young Generation in Asia-Pacific 2017, 20 May 2017, Hong Kong SAR **(The 3rd place for the Best Poster Award)**
8. **Zhang JH**, An WW, Au IPH, Chan ZYS, Cheung RTH (2016) Kinetics control in runners at different running speeds and slopes after completion of a gait retraining program. The 5th HKASMSS Student Conference on Sports Medicine, Rehabilitation and Exercise Science 2016, 26 November 2016, Hong Kong SAR
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10. **Zhang JH**, McPhail AJC, An WW, Naqvi QM, Chan DLH, Au IPH, Luk ATW, Chen TL, Cheung RTH (2016) Effects of a new running shoe design on the landing pattern and energy loss. The 21st Annual Congress of the European College of Sport Science, 6-9 July 2016, Vienna.
11. **Zhang JH**, An WW, Au IPH, Cheung RTH. (2015) Intra- and inter-subject analysis of the correlations between impact laoding rates and peak positive acceleration measured at different body sites during running.

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LIST OF ABBREVIATIONS

AnkAng: Ankle dorsiflexion angle

ANN: Artificial neural network

CoM: Centre of mass

DNNE: Decorrelated neural network ensembles

DR: Downhill running

FFS: Forefoot strike

FSA: Footstrike angle

GRF: Ground reaction force

LR: Level running

MAD: Mean absolute difference

MFS: Midfoot strike

PRS: Preferred running speed

PTS: Peak tibial shock

RCI: Reliable change index

RFS: Rearfoot strike

RMSE: Root mean square error

RRI: Running injury risk

SL: Stride length

THM: Time between heel and metatarsal

TS: Training speed

UR: Uphill running

VALR: Vertical average loading rate

VILR: Vertical instantaneous loading rate

VLR: Vertical loading rate

SECTION I
MAIN STUDIES OF THIS THESIS

Change is the end result of all true learning

-- Leo Buscaglia

The first section describes series of studies regarding the training effect of a current running gait retraining protocol. More specifically, these studies focused on the how the runners maintained the newly learned running gait when running conditions changed.

CHAPTER 1
INTRODUCTION

1.1 Gait retraining in running injury control

Distance running has become popular partly because of its association with longevity (Lee et al., 2017) and health (Lear et al., 2017). However, one drawback related to running is the risk of running-related injuries (RRIs). Previous studies reported that the annual RRI risk could be as high as 79% (Gent et al., 2007). As running can be modelled as repeated collisions between the body and the ground (McMahon and Cheng, 1990), faulty running biomechanics has been considered as one of the major risk factors to result in RRIs in runners.

Several previous studies have attempted to establish an association between injury risk and some biomechanical parameters (Worp et al., 2016). It has been recognised in multiple retrospective studies that a high vertical loading rate (Thijs et al., 2008; Worp et al., 2016) at initial contact could lead to RRIs such as patellofemoral pain (Thijs et al., 2008), tibial stress fractures (Milner et al., 2006; Pohl et al., 2008), and plantar fasciitis (Pohl et al., 2009). Some other biomechanical parameters associated with vertical loading rate are also considered as potential risk factors for RRIs, including peak tibial shock, which is measured using an accelerometer mounted in the distal tibia (Milner et al., 2006; Zhang et al., 2016).

Examination of these biomechanical parameters may provide insights and guidelines for running coaches and sports trainers to monitor the gait biomechanics of a runner and therefore may help reduce the injury risk. Moreover, measuring these parameters in real-time can provide feedback to runners to induce a self-regulated gait retraining (Crowell et al., 2010; Crowell and Davis, 2011).

Previous gait retraining programs adopt different sensory feedbacks, e.g., audio (Wood and Kipp, 2014) or visual (Cheung et al., 2018; Crowell et al., 2010; Crowell and Davis, 2011), and they vary in the number of training sessions, e.g. a single session (Crowell et al., 2010) or an eight-session training program (Chan et al., 2018b; Crowell et al., 2010). However, several training programs reported that runners were able to modify their running gait and reduce the impact loading upon the completion of the training (Chan et al., 2018b; Crowell et al., 2010; Crowell and Davis, 2011). Moreover, these gait retraining programs were shown effective in lowering injury risk (Chan et al., 2018b) and easing symptoms of RRIs (Cheung and Davis, 2011; Esculier et al., 2017). Thus, a structured gait retraining program has been considered a viable and systemic method to modify faulty running gait pattern and lower injury risk (Davis, 2017).

1.2 Research gaps in current gait retraining studies

Despite the positive effect reported in current gait retraining programs, several limitations should be addressed. Firstly, several gait retraining protocols only measure the target biomechanical parameter at one side of the lower limbs, and the training effect of the other limb was unassessed. Secondly, because current gait retraining requires a laboratory setting to measure the biomechanical parameter, the training sessions are usually conducted in a constraint environment. Feedback was given during treadmill level running at a constant running speed across all training sessions. Since the ability to translate a newly learned motor skill to other untrained environment is an important part of motor learning, the training effect translation in an unconstraint running environment remains unknown.

1.2.1 Inter-limb translation

An important assumption in gait retraining is the symmetry of human gait. However, such an assumption is unwarranted. Kinetic parameters have shown a high level of asymmetry during running (Radzak et al., 2017; Zifchock et al., 2006). It has been reported that the right and left peak tibial shock experienced a difference at 31.7% of the mean value of both limbs (Zifchock et al., 2006). Due to a high asymmetry level, whether gait retraining aiming to reduce peak tibial shock on one side of lower extremity would lead to an increase on the other side is unknown.

1.2.2 Inter-condition translation: to varied speeds, slopes, and overground running

While the training condition was constrained, a runner would experience overground running with variance in running speed and slope in their daily training sessions or endurance running competition.

Past gait retraining studies usually treated speed as a confounding factor (Cheung et al., 2018; Crowell and Davis, 2011) because speed has shown associated with several commonly used biomechanical feedback parameter, e.g., vertical loading rates (Chan et al., 2018b) and peak tibial shock (An et al., 2015; Zhang et al., 2016). Thus, whether trained runners be able to exhibit the newly learned running gait at a different speed is questionable. If the training effect is speed-specific, runners after gait retraining may not benefit from a lower impact during regular running outside the laboratory environment.

Running on slopes has been reported to lead to changes in landing pattern (Lussiana et al., 2013), vertical stiffness (An et al., 2015; Hunter, 2003), and temporal-spatial parameters (Padulo et al., 2012), which may all contribute to changes in lower extremity loading (Vernillo et al., 2016). Thus, it could be challenging for the runners to maintain softer footfalls while running on slopes after a course of gait retraining conducted on the level surface.

Additionally, running mode (i.e., treadmill vs. overground) could potentially affect the translation of the training effect. Although previous studies reported similar joint kinematics (Fullenkamp et al., 2017), ground reaction forces (Firminger et al., 2018; Kluitenberg et al., 2015), and peak tibial shock (Montgomery et al., 2016) between the two running modes, treadmill running was considered requiring more voluntary gait pattern control than overground running (Lindsay et al., 2014), associating with shorter stride length and higher cadence (Riley et al., 2008). Whilst there are potential differences between the two running modes, it may be ambiguous that how much the runners can translate the newly learned running pattern from treadmill to overground running following an indoor gait retraining program.

1.2.3 Motor strategies adopted after gait retraining

Peak tibial shock is a widely used biomechanical feedback in several gait retraining protocols to provide kinetics information (Cheung et al., 2018; Crowell et al., 2010; Crowell and Davis, 2011; Wood and Kipp, 2014). However, changes in kinematics and temporal-spatial parameters after using this kinetic-based gait retraining program were yet unclear. Previous studies reported runners could reduce the peak tibial shock through increasing step rate (Lenhart et al., 2014; Willy et al., 2016). Concerning running kinematics, runners who land with forefoot or midfoot showed lower peak tibial shock than those who land with rearfoot (Glauberman and Cavanagh, 2014). These changes in the temporal-spatial or kinematic parameters could be considered as a motor strategy adopted by the runners after training. Since the instructions given in gait retraining sessions might also affect a runner's motor strategy (Wulf et al., 2010), runners are often told to "land softer" without given any further information towards their running gait in several gait retraining programs (Crowell and Davis, 2011). It is highly possible that runners adopted different motor strategies during training. However, little is known about whether a particular motor strategy associated with the effect of the gait retraining and the translation of training effect into different running conditions.

1.3 Statement of research questions

Although previous studies showed a positive effect of running gait retraining, the understanding of the motor learning process and the translation of the training effect is incomplete. This study aimed to assess the motor learning translation of an established running gait retraining program which used peak tibial shock as biomechanical feedback. The translation focused in this thesis included 1) inter-limb translation; 2) inter-speed translation; 3) inter-slope translation; and 4) treadmill-overground translation.

The first study (Chapter 4) validated the association between peak tibial shock and vertical loading rates when running at various speeds and slopes. Based on this association, the second study (Chapter 5) addressed the inter-limb and inter-speed translation, while the third study (Chapter 6) addressed the inter-speed and inter-slope translation. In order to understand the motor strategies adopted by runners during gait retaining, the fourth study (Chapter 7) was conducted to investigate temporal-spatial and kinematics changes. A general conclusion was given in Chapter 8.

1.4 Objectives & Hypotheses

The present work consists of four studies centred around gait retraining and translation of training effect. The objectives and hypotheses of each study are stated here.

Chapter 4

Objectives: This study sought to establish the association between vertical loading rates and peak shock measured at the lateral malleoli and the distal tibia in different running conditions.

- **Hypothesis 1** Peak shock measured at distal tibia associated with vertical loading rates within each subject.
- **Hypothesis 2** Such an association could be maintained in varied running speeds and slopes.

Chapter 5

Objectives: This study sought to assess the effect of running gait retraining program on the untrained limb during untrained running speeds.

- **Hypothesis 1** The current training protocol would facilitate a motor learning translation to the untrained lower extremity.
- **Hypothesis 2** After training, runners would be able to reduce the peak tibial shock during running at untrained speeds.

Chapter 6

Objectives: This study sought to examine the peak tibial shock during treadmill and overground running on different slopes before and after the current treadmill running gait retraining program.

- **Hypothesis 1** There would be training non-respondents, who failed to reduce the peak tibial shock during treadmill level running after gait retraining.
- **Hypothesis 2** Runners who were responsive to the gait retraining would maintain the training effect in untrained conditions, including overground and slope running.

Chapter 7

Objectives: This study sought to identify motor strategies adopted by the runners after the current treadmill running gait retraining program. This study did individual analysis to assess the how these changes would affect the motor learning translation to varied running speeds and slopes.

- **Hypothesis 1** Runners showed different strategies after the training, including changes in stride length and footstrike angle.
- **Hypothesis 2** Runners who adopted multiple strategies showed better training effect translation when running at varied speeds and slopes.

CHAPTER 2
LITERATURE REVIEW

2.1 Gait retraining protocol

Feedback-based gait retraining has been widely applied in running-related injury prevention (Barrios et al., 2010; Chan et al., 2018b; Crowell and Davis, 2011) and rehabilitation for injured runners (Cheung and Davis, 2011). The design of a gait retraining protocol falls into two questions, including 1) How to choose a feedback provided to the runner; and 2) How long should the runner receive this feedback. This section of literature review will introduce previous findings addressing these two questions. We hope to provide insights for the optimization of the gait retraining protocol in the future.

2.1.1 To choose a feedback

The focus of attention induced by the feedback could affect motor learning performance (Shea and Wulf, 1999). According to Wulf and her colleagues (Shea and Wulf, 1999; Wulf et al., 2002; Zachry et al., 2005), the feedback that directs a subject's attention to the production of body movement is called an internal focus of attention. In contrast, external focus of attention refers to the feedback that directs to an external effect that is produced as a result of the body movement. Series of studies reported that feedback leading to an external focus of attention demonstrated better performance in motor skill acquisition (Wulf and Su, 2007), including the retention of a newly learned running gait after a course of gait retraining (Chan et al., 2018b). The benefit of an external focus of attention could be explained by the "constrained action hypothesis" (McNevin et al., 2003; Wulf et al., 2001). More specifically, focusing on the movement effects promotes the utilization of automatic processes, and focusing on movements of body segments leads to a more conscious type of control. Based on Wulf et al.'s hypothesis, an increased conscious control constrains the motor system and interrupts automatic control processes.

Biofeedback used in gait retraining was usually measured at one side of the body (Clansey et al., 2014; Crowell and Davis, 2011; Wood and Kipp, 2014; Zhang et al., 2019). The other side of brain hemisphere would process the information based on the feedback and control the body movement (Springer and Deutsch, 1997). It has been hypothesized that the left brain might be more sensitive in dealing with control of kinetic feedback (Harrington and Haaland, 1991; Sainburg, 2002), while the right brain might be more responsive to kinematic feedback (Sainburg, 2002; Stöckel and Wang, 2011). Such hypothesis has been tested in a previous mechanistic study (Sainburg, 2002). It showed that kinetic feedback provided from the right extremity could enhance the motor learning translation, while the same kinetic feedback measured at the left limb did not show a similar result (Sainburg, 2002).

2.1.2 To design a training protocol

The training design, such as training intensity and duration, can also affect the effect (Davis, 2017). This section provides a summary of the previous gait retraining studies, which used peak tibial shock (PTS) as a biofeedback (Table 2.1). PTS is considered as a kinetic feedback that reflects the effect of movements. Thus, real-time information about PTS value was considered to associate with an external focus of attention (Zhang et al., 2019).

Among the seven studies listed in Table 2.1, three of them used a single-session training protocol and reported that the PTS was reduced by 8.47-32.6% immediately after training (Creaby and Franettovich Smith, 2016; Townshend et al., 2017; Wood and Kipp, 2014), and in 1-week follow-up (Creaby and Franettovich Smith, 2016). Multi-session protocols reported a greater reduction in the PTS (28.5-48.0%) than those single-session studies (Bowser et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011; Zhang et al., 2019). Three out of the four multi-session training protocols adopted a program featuring an increasing training time and fading feedback (Crowell and Davis, 2011; Zhang et al., 2019), which was considered beneficial in preventing feedback reliance (Winstein, 1991).

In a study that reported the lowest amount of PTS reduction (0.5 g reduction in PTS), investigators affixed the accelerometer on the left tibia (Wood and Kipp, 2014), whilst most remaining studies measured PTS at the right tibia (Clansey et al., 2014; Creaby and Franettovich Smith, 2016; Zhang et al., 2019). The amount of reduction in the PTS reported in that particular study using a sensor on the left limb (Wood and Kipp, 2014) was close to the minimal detectable change (0.51 g) calculated by another study (Townshend et al., 2017). A possible reason for the little reduction could be due to a lower training threshold adopted in Wood and Kipp's study (2014). They only aimed for a 15% off from the baseline measurement. Another explanation could be based on the motor control theories, i.e., the left limb is controlled by the right brain hemisphere. Since right brain hemisphere was less responsive to the kinetic parameters (Sainburg, 2002; Stöckel and Wang, 2011), such training design could result in a less efficient motor learning.

Table 2.1 Summary of previous studies which used peak tibial shock (PTS) measured at distal tibial for running gait retraining

Study (N)	Testing speed	Training protocol					PTS reduction
		Training speed	Training sessions	Training threshold (Compared to pre-training test)	Training time	Feedback time	
Zhang et al., 2019 (N = 15)	Self-selected	Self-selected	8 sessions in 2 weeks	20% off	Gradually increased from 15 to 30 min	Faded feedback in the last four sessions	28.5%
Bowser et al., 2018 (N = 19)	3.7m/s	Self-selected	8 sessions in 3 weeks	50% off			32%
Crowell and Davis, 2011 (N = 10)	3.7 m/s	Self-selected	8 sessions in 2 weeks	50% off			48%
Clansey et al., 2014 (N = 15)	3.7 m/s	3.7 m/s	6 sessions in 3 weeks	50% off	35 min for every session	20 min feedback in the middle	30.7%
Townshend et al., 2017 (N = 12)	3 m/s	3 m/s	Single session	50% off	20 min	10 min feedback running, 10 min non-feedback running	32.6%
Creaby and Franettovich Smith , 2016 (N = 22)	3 m/s	3 m/s	Single session	50% off			18.9%
Wood and Kipp, 2014 (N = 9)	Self-selected	Self-selected	Single session	10-15% off	25 min	5 min warm-up followed by 2 rounds of training, which included 5-min feedback and 5-min no-feedback running	8.47%

2.2 Effect of running speed and slope to running gait

In general, a faster running speed and a downhill running condition were shown associated with higher lower extremity loading. Changes in impact loading could be a result of an altered landing pattern, a longer stride, or because of a change in vertical displacement of body centre of mass. This session of literature review focused on the possible explanations for the increased impact loading when running at a faster speed or downhill. We hope to obtain a better understanding of the association between kinematics and kinetics changes in varied running conditions.

2.2.1 Effect of speed

As speed increased, runners experience greater lower extremity loading, which can be reflected by several kinetic parameters such as impact peak (Hamill et al., 1983), vertical loading rates (VLR) (Nigg et al., 1987), and peak tibial shock (PTS) ((Boey et al., 2017). The increased lower extremity loading can be a result of longer strides during a faster running speed (Clarke et al., 1985; Hobara et al., 2012). Although runners may increase stride length and stride frequency at the same time when speed increases, (Hahn et al., 2017; Mercer et al., 2002), runners tend to adjust stride length, i.e., making longer strides, rather than increase the cadence to achieve a higher running speed (Dorn et al., 2012; Fukuchi et al., 2017).

Whether the increased impact loading at fast speed could be a result of an increased footstrike angle (FSA) was not clear. Past studies reported inconsistent findings regarding the changes in FSA with running speed (Breine et al., 2014; Cheung et al., 2016; Fukuchi et al., 2017; Hasegawa et al., 2007; Larson et al., 2011). Generally speaking, runners tend to reduce FSA, i.e., to landing with non-RFS, at a higher speed (Cheung et al., 2016). However, a recent study showed that less than 25% of runners lowered their FSA when running at a fast pace (5.1 m/s) (Breine et al., 2018). It is possible that runners' FSA can be affected by a series of factors, including footwear (Cheung et al., 2016; Lieberman et al., 2010), running experience (Hasegawa et al., 2007), speed (Breine et al., 2018; Cheung et al., 2016), and other external factors.

2.2.2 Effect of slope

Downhill running has been associated with an increased VLR (VLR) (An et al., 2015; Gottschall and Kram, 2005; Telhan et al., 2010). On the contrary, uphill running has been associated with lower VLR (An et al., 2015; Gottschall and Kram, 2005; Kowalski and Li, 2016). Such findings are more consistent when the surface inclination exceeds 10% gradient (An et al., 2015; Gottschall and Kram, 2005), but it becomes equivocal when running on a surface with less than 10% gradient (Gottschall and Kram, 2005; Telhan et al., 2010). A comparison of results from different studies has been listed in Table 2.2.

The reduced VLR during uphill running can be a result of shortened stride length (Dewolf et al., 2016; Gottschall and Kram, 2005; Telhan et al., 2010), higher stride frequency (Schubert et al., 2014), and a reduced vertical displacement of centre of mass (An et al., 2015; Dewolf et al., 2016). On the other hand, changes in the footstrike pattern can also lead to a reduction in the VLR during uphill running (Lieberman et al., 2010). Studies reported that recreational runners tend to land with a RFS pattern during level or downhill running but gradually shift to a MRS or FFS pattern during uphill running (Gottschall and Kram, 2005; Lussiana et al., 2013).

Table 2.2 Summary of studies investigating the effect of running slopes on stride length, contact time, footstrike angle (FSA), and vertical loading rates (VLR)

Study	N	Speed (km/h)	Slope (%)	Stride length	Contact time	FSA (°)	VLR (g)
(Park et al., 2019)	15	11.5	-10.5	⇔	⇔	⇔	NA
			-15.8	⇔	⇔	⇔	NA
(Kowalski and Li, 2016)	15	10.8	-10.5	NA	NA	Comparable ankle angle at initial contact across different running slopes	⇔
			-15.8	NA	NA		⇔
			+10.5	NA	NA		⇓
			+15.8	NA	NA		⇓
(Dewolf et al., 2016)	10	7.9-18	-5.2	⇑	⇔	NA	NA
			-10.5	⇑	⇔	NA	NA
			-15.8	⇑	⇔	NA	NA
			+5.2	⇓	⇔	NA	NA
			+10.5	⇓	⇔	NA	NA
			+15.8	⇓	⇔	NA	NA
(An et al., 2015)	20	8.0	-10.0	NA	NA	⇔	⇑
			+10.0	NA	NA	⇔	⇓

Continued in the next page

Table 2.2 Continue

Study	N	Speed (km/h)	Slope (%)	Stride length	Contact time	FSA (°)	VLR (g)
(Lussiana et al., 2013)	14	10.0	-8.0	NA	⇔	⇔	NA
			-5.0	NA	⇔	⇔	NA
			-2.0	NA	⇔	⇔	NA
			+2.0	NA	⇔	⇔	NA
			+5.0	NA	⇔	⇔	NA
			+8.0	NA	⇔	⇓	NA
(Telhan et al., 2010)	19	12.0	-7.0	⇔	NA	NA	⇑
			+7.0	⇓	NA	NA	⇔
(Gottschall and Kram, 2005)	10	10.8	-15.8	⇔	⇔	RFS landing pattern during downhill conditions and +5.2% uphill running condition	⇑
			-10.5	⇔	⇔		⇑
			-5.2	⇔	⇔		⇔
			+5.2	⇔	⇔		⇔
			+10.5	⇔	⇔	Gradually switch to MFS landing pattern	⇓
			+15.8	⇓	⇔		NA

CHAPTER 3
METHODOLOGY

3.1 Measurement of tibial shock

Tibia shock was measured in Chapter 4-7 using the following method. The tibial shock was recorded using a wireless tri-axial accelerometer (Model 518, ±24 g, Noraxon, Arizona, USA) with a 10^{-3} g resolution and sensitivity of ±0.17 V/g (Figure 3.1). The accelerometer weights 5.7 g, and the dimensions for the accelerometer have been provided in Figure 3.1.

To collect the tibial shock data, the accelerometer was attached onto the anterior-medial aspect of distal tibia (Figure 3.2), right above the medial malleolus. The accelerometer was affixed onto the body with double sided tape and then securely wrapped with straps. The acceleration data was sampled at 1,000 Hz using a commercial software (Noraxon MR 3.10, Arizona, USA), and then filtered with a Butterworth low-pass filter at 50 Hz (Zhang et al., 2016). Peak tibial shock was identified as the maximum value during the stance phase (Crowell and Davis, 2011; Milner et al., 2006).

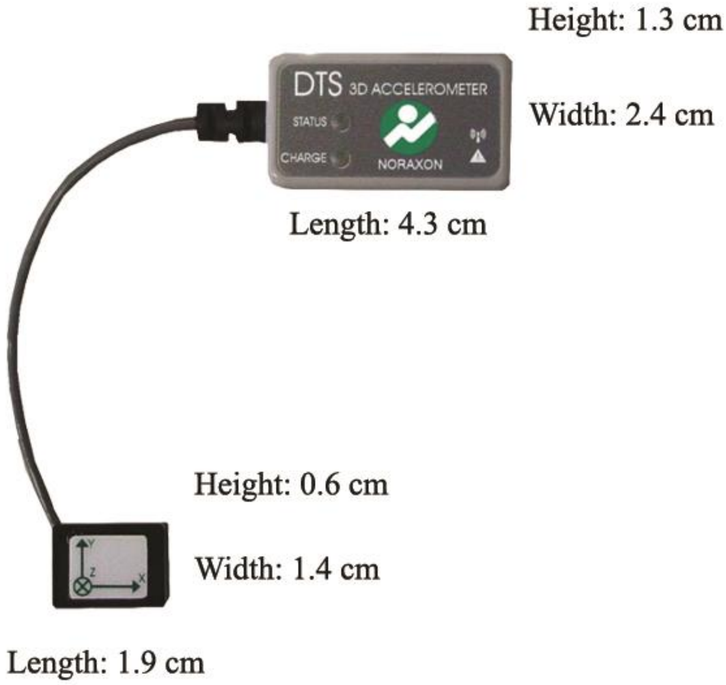

Figure 3.1 Dimension of the wireless tri-axial accelerometer used in this thesis

Figure 3.2 Placement of the accelerometer on the distal tibia

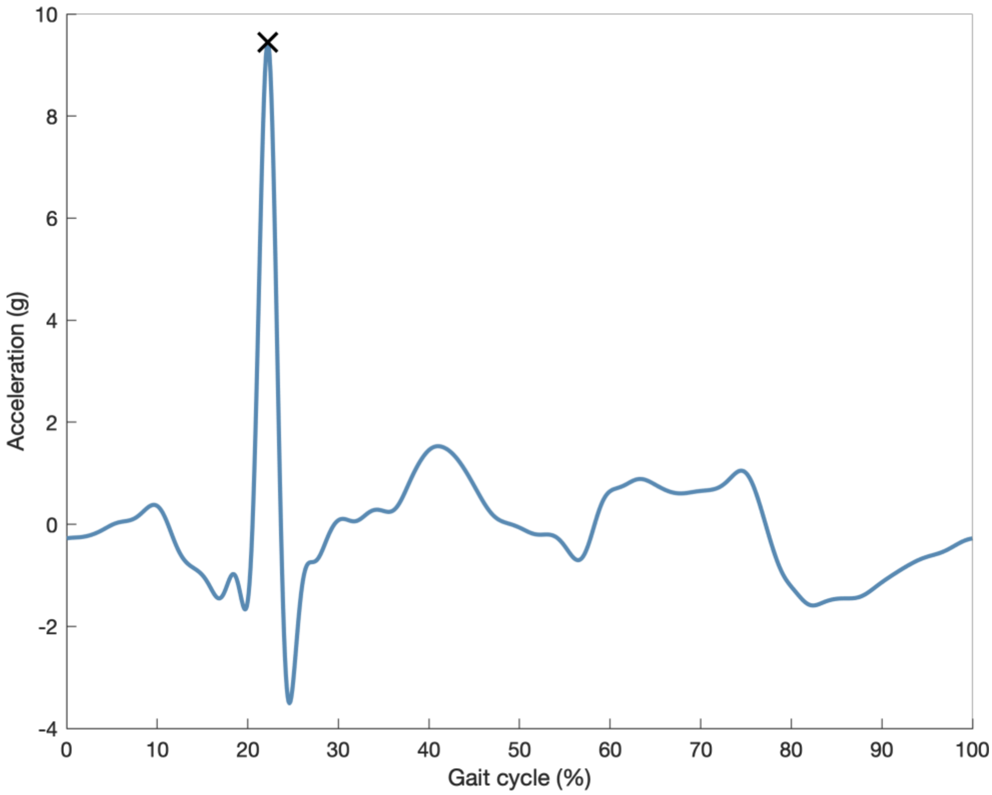

Figure 3.3 Tibial shock in one stride, with peak tibial shock marked as a cross

3.2 Gait retraining protocol used in this thesis

The running retraining protocol used in this thesis (Chapter 4-7) is based on a previously established protocol described by Crowell and Davis (Crowell and Davis, 2011). It is a 2-week 8-session gait retraining program with a fading real-time biofeedback protocol (Crowell and Davis, 2011).

A pre-training test was arranged to determine the training target for each participant. During the pre-training test, participants were asked to run on a treadmill at a self-selected running speed for 3 minutes. This self-selected speed would be used as the training speed in all the training sessions. The tibial acceleration was recorded during the last minute running, and the peak tibial shock was extracted as described in Chapter 3.1. The training target was then set at 80% of their average peak tibial shock value measured during the pre-training test, which was based on a previous running retraining study (Cheung et al., 2018).

Figure 3.4 shows the setup of the running retraining. A monitor was placed 1 meter in front of the treadmill at a participant's eye level. During training, continuous tibial acceleration measured at the right limb was provided to the participants as a real-time biofeedback. A line was displayed to indicate the training target. Each participant ran at their training speed on a treadmill and was instructed to "land softer" in order to maintain his/ her peak tibial shock below the threshold. As shown in Figure 3.5, the total training time increased from 15 to 30 minutes during the 8-session training, while the feedback was gradually removed in the last four sessions. Such design was to prevent reliance on biofeedback, and it was shown beneficial to enhance motor learning (Winstein, 1991).

Figure 3.4 Setup of the current running retraining protocol

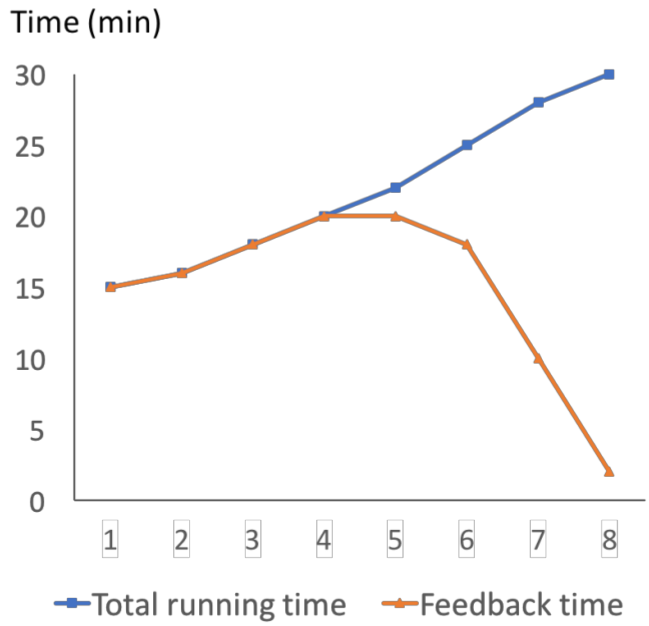

Figure 3.5 Training time and feedback time used in the current running retraining protocol

3.3 Marker placement to calculate footstrike angle

The footstrike angle (FSA) was a parameter used in the studies described in Chapter 7-9. The method to calculate FSA was based on a previous study (Altman and Davis, 2012). In brief, two reflective markers were placed on the heel and the second metatarsal head (Figure 3.6). The participants were asked to run on an instrumented treadmill (AMTI, MA, USA). The maker trajectories were captured using an eight-camera motion capture system (Vicon, Oxford, UK), and synchronized ground reaction force data were recorded at 1,000 Hz.

The FSA was formed by a line joining the two markers and an imaginary horizontal line parallel to the running surface at initial contact (Figure 3.6a). The time of initial contact was defined when the vertical ground reaction force reached a 20 N threshold (McCallion et al., 2014). To compensate for the variance of marker placement, a static trial was collected, and the FSA during the static trial was considered as an offset, which was subtracted from the FSA in running trials. The cutoff values for rearfoot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS) were based on a previous study (Altman and Davis, 2012). It was suggested that a strike with FSA in between -1.6° and 8° would be considered as a MFS, with lower than -1.6° being FFS and higher than 8° being RFS.

a

b

c

Figure 3.6. Definition of footstrike angle (FSA, a), and classifications of rearfoot strike (a), midfoot strike (b), forefoot strike (c) landing patterns

CHAPTER 4
COMPARISON OF THE CORRELATIONS BETWEEN VERTICAL LOADING RATES AND PEAK SHOCK MEASURED AT TWO DIFFERENT BODY SITES: INTRA- AND INTER-SUBJECT ANALYSIS

This chapter is based on the publication on *Gait & Posture* in 2016. The copyright permission has been attached in Appendix I.

4.1 Objectives & Hypotheses

Objectives: This study sought to establish the association between vertical loading rates (VLRs) and peak shock measured at the lateral malleoli and the distal tibia in different running conditions.

- **Hypothesis 1.1** Peak shock measured at distal tibia associated with vertical loading rates within each subject.
- **Hypothesis 1.2** Such an association could be maintained in varied running speeds and slopes.

4.2 Methods

4.2.1 Subjects and procedures

Ten healthy adults (8 males and 2 females; age=23.6±3.8 years; height=1.73±0.08 m; mass=66.1±12.7 kg) free from any active lower-extremity injuries were recruited. All the subjects signed an informed consent form and the experiment was approved by the concerning institutional review board.

Four lightweight accelerometers (Model 7523A5, 0-400 Hz frequency range, 50g range, Dytran Instruments, CA, USA) were securely taped on both sides of the lateral malleoli and anteromedial aspect of the distal tibias (Figure 4.1). All the subjects conducted nine randomized running conditions on an instrumented treadmill (AMTI, Watertown, MA, USA), with differences in speed (usual speed; +15% of usual speed; and -15% of usual speed) and inclination surfaces (flat; 10% inclined; and 10% declined). Each running trial lasted for two minutes with 1-minute rest to avoid fatigue. Customized LabVIEW codes (version 8.6, National Instruments, Austin, TX, USA) were used to capture the vertical ground reaction force and acceleration data.

4.2.2 Data analysis

Ground reaction force and acceleration data were recorded at 1,000 Hz, filtered at 50 Hz with a fourth order Butterworth lowpass filter (Cheung and Davis, 2011). Average (VALR) and instantaneous vertical loading rate (VILR) were obtained by the method previously described (Crowell and Davis, 2011), and normalized by body mass. VALR was the slope of the line through the 20% point and the 80% point of the vertical impact peak. VILR was the maximum slope of the vertical ground reaction force curve in the same region. Landing peak acceleration (PA) was defined as the maximum positive acceleration that occurred during the early stance phase of running (Crowell and Davis, 2011). VALR, VILR, and landing PA at different body sites were identified in 40 consecutive steps in each running trial.

4.2.3 Statistical analysis

All the data were processed using SPSS.21® statistics software of package (Chicago, IL, USA). Global alpha was set at 0.05. Intra-subject correlations between VALR, VILR, and PA measured at different body sites were analysed using Pearson's *r*. Paired-t tests were used to compare the Pearson's *r* between distal tibia and lateral malleoli among the 10 subjects.

Bland and Altman's method (Bland and Altman, 1995) was used to examine the inter-subject variance in the association between PA and VLRs. Multiple regressions were performed, and subject was treated as a categorical factor using dummy variables to assess the variation brought by each subject on prediction of VLRs, expressing as the unstandardized coefficient (B). Any subject with significant ($p<0.05$) B was considered to have a significant variance with the pooled regression curves. Paired-t tests were used to compare the B values between distal tibia and lateral malleoli among the 10 subjects.

Figure 4.1 Accelerometers taped to the subject's lateral malleoli and the anteromedial aspect distal tibia

4.3 Results

The results of intra-subject correlations between peak acceleration (PA) and vertial loading rates (VLRs) in all the nine running conditions were shown in Table 4.1 and Table 4.2. PA at the lateral malleoi and the distal tibia demonstrated a moderate to excellent positive correlation with VALR and VILR (r=0.486-0.950, p<0.001). The PA measured at the lateral malleoli showed stronger association compared to that at the distal tibia (both p=0.04).

The inter-subject analysis between PA and VLRs were shown in Figure 4.2 (a-d), with each subject represented by a colored line, and the pooled regression curve was shown as a line with dots at both ends. Five out of 10 subjects had significant variance in the correlation between PA measured at the distal tibia (Figure 4.2a and b, B=3.88±3.09 BW/s in VALR; B=5.69±3.05 BW/s in VLIR). Similarly in PA measured at the lateral malleoli, seven and eight out of 10 subjects had significant variance with the pooled VALR and VILR correlation curves respectively (Figure 4.2c and d, B=5.24±2.85 BW/s in VALR; B=6.67±2.83 BW/s in VLIR). No significant difference was observed in the B values between PA measured at the lateral malleoli and the distal tibia (both p > 0.05).

Table 4.1 Mean and SD values for each subject and intra-subject correlation coefficients (r) between peak shock and VLRs

	Measured value (mean (SD))				Correlation coefficient (r)			
Subject	Landing PA at distal tibia (g)	Landing PA at lateral malleoli (g)	VALR (BW/s)	VILR (BW/s)	Landing PA at distal tibia		Landing PA at lateral malleoli	
					VALR	VILR	VALR	VILR
1	13.71(2.29)	13.10(2.42)	88.37(19.31)	131.30(27.62)	0.546**	0.584**	0.617**	0.647**
2	10.15(2.22)	10.05(2.18)	79.82(25.87)	123.89(41.12)	0.793**	0.779**	0.950**	0.948**
3	7.99(1.88)	7.26(1.36)	42.82(12.91)	67.98(15.86)	0.778**	0.771**	0.878**	0.887**
4	7.62(2.19)	6.97(1.68)	52.15(20.01)	83.38(28.11)	0.913**	0.898**	0.863**	0.879**
5	6.08(1.08)	5.31(1.07)	30.19(9.15)	45.63(13.56)	0.580**	0.583**	0.736**	0.682**
6	13.06(2.85)	11.33(2.36)	68.04(18.85)	106.86(25.28)	0.495**	0.528**	0.595**	0.633**
7	7.12(1.74)	6.37(0.84)	30.78(9.03)	46.06(14.24)	0.556**	0.577**	0.561**	0.608**
8	8.75(1.87)	7.62(1.28)	70.28(17.17)	100.46(24.43)	0.802**	0.807**	0.926**	0.934**
9	7.27(1.81)	7.25(1.44)	41.17(15.81)	65.84(24.93)	0.638**	0.737**	0.688**	0.815**
10	6.28(1.47)	5.71(1.01)	30.82(3.96)	43.36(7.72)	0.486**	0.547**	0.699**	0.862**

* $p < 0.05$

** $p < 0.00$

Table 4.2 Pearson's correlation coefficients (r) between peak acceleration (PA) and vertical loading rates (VLRs) in nine running conditions

Condition		PA at distal tibia		PA at lateral malleoli	
		VALR	VILR	VALR	VILR
Level	Usual speed	0.75**	0.77**	0.81**	0.83**
	15% faster	0.72**	0.74**	0.79**	0.82**
	15% slower	0.74**	0.76**	0.81**	0.83**
Uphill	Usual speed	0.76**	0.77**	0.81**	0.83**
	15% faster	0.74**	0.76**	0.80**	0.82**
	15% slower	0.75**	0.77**	0.82**	0.84**
Downhill	Usual speed	0.75**	0.76**	0.81**	0.83**
	15% faster	0.73**	0.74**	0.81**	0.82**
	15% slower	0.74**	0.76**	0.81**	0.83**

* $p < 0.05$

** $p < 0.00$

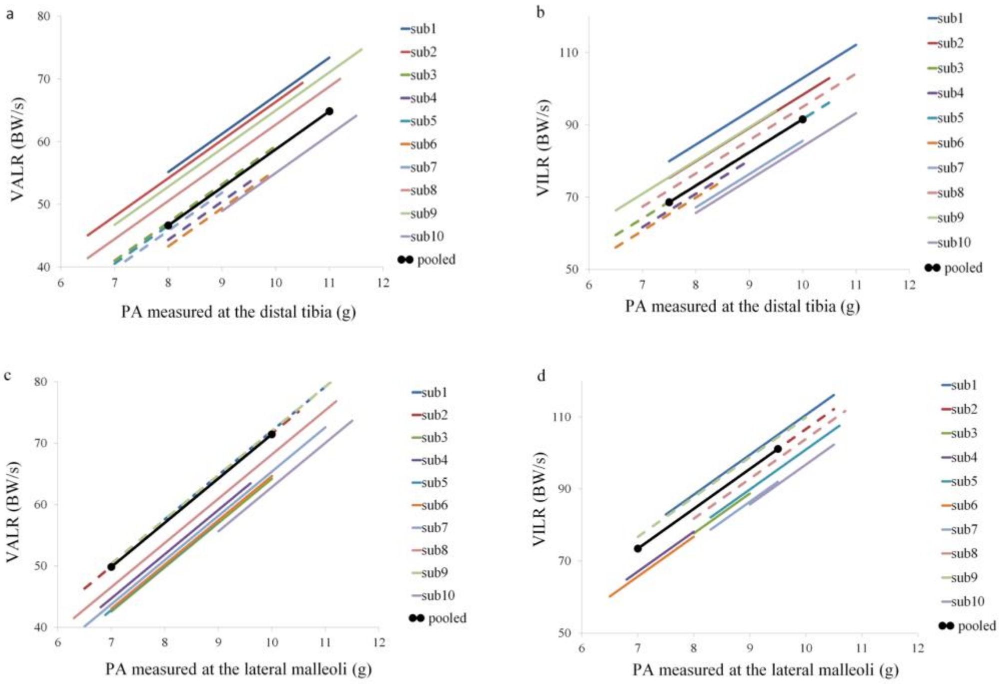

Figure 4.2 Correlation between VLRs and PA measured at distal tibia (a-b) and lateral malleoli (c-d), showing the variation between the subjects

4.4 Discussion

This study examined the intra- and inter-subject association between PA and VLRs. The findings demonstrated a moderate to strong intra-subject correlations between PA at the distal tibia and the lateral malleoli with VLRs across different running conditions. PA measured at the lateral malleoli was better associated with VLRs than that at the distal tibia. Based on this finding, wireless accelerometers can be used as a substitute measure of VLRs in outdoor running enviroment. However, PA measured at different body sites may not be able to accurately predict VALR and VILR between different subjects.

The higher intra-subject association between PA at the lateral malleoli and the distal tibia with VLRs may relate to the proximity of the measurement site with the impact, which is comparable with previous studies (r=0.70-0.92) (Fortune et al., 2014; Rowlands and Stiles, 2012). The correlation coefficient of the present study were relatively lower compared to the previous walking trials. This may mainly due to the increased variance in the ground reaction force in the transition from walking to running, as observed in study by Neugebauer et al. (Neugebauer et al., 2014).

High inter-subject variances were observed in the present study, with unstandardized coefficients of 8.595 BW/s in VALR, and 11.367 BW/s in VILR. Because of the inter-subject variance, runners expressing same PA measurement at a certain body site may experience different level of VLRs. While we found no significant difference in the inter-subject variance between the selected measuring sites, future study is warranted to explore a location for a better measurement.

In this study, we did not collect kinematics data. Further studies are warranted to investigate the cause for such inter-subject variance. Moreover, the present study assessed the correlation between VLRs and PA in a group of young adults, among which male subjects took a major part of the sample. Future studies including a balanced gender proportion are needed.

4.5 Conclusion

Based on the results of the present study, wireless accelerometers can be used to estimate VLRs within an individual in outdoor running environment. Due to high inter-subject variance, comparison of PA between subjects should be made with caution.

4.6 Project dissemination

Journal publication

Zhang JH, An WW, Au IPH, Chen TL, Cheung RTH. (2016) 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

Conference proceeding

Zhang JH, An WW, Au IPH, Cheung RTH. (2015) Intra- and inter-subject analysis of the correlations between impact laoding rates and peak positive acceleration measured at different body sites during running. Hong Kong Physiotherapy Association Conference. Oct 3-4, Hong Kong SAR

CHAPTER 5

REDUCTION OF PEAK TIBIAL SHOCK AFTER RUNNING GAIT RETRAINING: COMPARISONS BETWEEN TRAINED AND UNTRAINED LIMB, TRAINED AND UNTRAINED RUNNING SPEEDS

5.1 Objectives & Hypotheses

Objectives: This study sought to assess the effect of running gait retraining program on the untrained limb during untrained running speeds.

- **Hypothesis 2.1** The current training protocol would facilitate a motor learning translation to the untrained lower extremity.
- **Hypothesis 2.2** After training, runners would be able to reduce the peak tibial shock during running at untrained speeds.

5.2 Methods

5.2.1 Participants

A prior sample size estimation was conducted using the peak tibial shock data reported in a previous study (Cheung et al., 2018). Thirteen runners were required to attain a power level at 0.8 for this study. Recreational runners aged between 18 and 50 years old from the local running club were recruited. They should be recreational runners with weekly mileage higher than 15 km for 2 years, and were free from any active injury upon enrolment (Cheung et al., 2018). Eighteen runners (6 females, age = 41.7 ± 5.9 years, body mass = 60.7 ± 9.6 kg, body height = 1.66 ± 0.06 m) were invited for the further assessment. Verbal and written informed consents were obtained from all the runners prior to the experiment, which was reviewed and approved by the Institutional Review Board of the Hong Kong Polytechnic University.

5.2.2 Data collection

All participants wore their usual running shoes during the assessments and all training sessions. The preferred running speed of each participant was measured during a 5-minute self-paced treadmill running (Chen et al., 2016) and it was used as the training speed (TS). A pre-training assessment including three trials was then conducted and all the participants were asked to run on an instrumented treadmill (AMTI, Watertown, MA, USA) at TS, 110% TS, and 90% TS in a randomized order. Two wireless accelerometers (± 24 g, Noraxon, Scottsdale, AZ, USA) were firmly affixed onto the anterior-medial surface of bilateral distal tibias with the z-axis alongside the longitudinal axis of tibia (Crowell and Davis, 2011). During each running trial, participants were asked to run for three minutes (Cheung et al., 2018) and the vertical acceleration data were collected at 500 Hz.

The acceleration data were then filtered at 50 Hz with a fourth order Butterworth filter (Zhang et al., 2016). The peak tibial shock in the last 20 footfalls in each trial were then identified, with 10 footfalls from each side. To avoid the floor effect, only 13 out of 18 runners who met the required running experience and weekly mileage (3 females and 10 males; age = 41.1 ± 6.9 years, body mass = 61.0 ± 7.8 kg, body height = 1.66 ± 0.06 m, TS =

2.8 ± 0.2 m·s^{-2}, running experience = 6.8 ± 4.4 years, weekly mileage = 30.7 ± 22.2 km), with average peak tibial shock higher than 8 g were invited to the gait retraining program (Crowell and Davis, 2011). This cut-off value was chosen since it is one standard deviation (1.66 g) above the mean peak tibial shock value (5.81 g) in a group of uninjured young adults (Milner et al., 2006).

5.2.3 Gait retraining

After the pre-training assessment, all the included participants underwent a 2-week 8-session gait retraining program with a previously established protocol (Crowell and Davis, 2011). As shown in Figure 5.1, during training, continuous right tibial acceleration was displayed on a screen positioned in front of a treadmill, and a line was placed across the screen at the training target value. The training target value was set at 80% of the average peak tibial shock measured in the pre-training assessment (Cheung et al., 2018). The 20% reduction could bring the tibial shock within one standard deviation of the mean peak tibial shock value measured from a group of uninjured runners (Crowell and Davis, 2011; Milner et al., 2006; Zifchock et al., 2006). Participants ran at their TS on a treadmill and were instructed to "land softer" to maintain their peak tibial shock below the line. The training time increased from 15 minutes to 30 minutes during the 8-session training, while the feedback was gradually removed in the last four training sessions.

5.2.4 Post-training assessment

A post-training assessment was conducted to all the participants within one week upon completion of the gait retraining program (Cheung et al., 2018). The testing procedure was identical to the pre-training assessment.

5.2.5 Statistical analysis

Repeated measures ANOVA with 2*2*3 (TRAINING*SIDE*SPEED) design were used to analyze the peak tibial shock between two sides before and after the running gait retraining at different speeds. To further compare the amount of reduction in peak tibial shock between both limbs and among different running speeds, the difference in peak tibial shock before and after the gait retraining were calculated and compared using repeated measures ANOVA with a 2*3 (SIDE*SPEED) design. When indicated, post-hoc comparisons with Bonferroni correction were conducted. The effect sizes of training were calculated using Cohen's d, and the benchmarks for a small, medium, and large effect size were set at 0.2, 0.5, 0.8 (Cohen, 1992). Global alpha was set at 0.05.

Figure 5.1 Example of real-time tibial acceleration provided to the runners as a biofeedback during gait retraining

5.3 Results

No significant TRAINING*SIDE*SPEED interaction was found ($F(1,1,12) = 1.196$, $p = 0.339$), while the TRAINING effect did not interact with SPEED ($F(1,12) = 1.125$, $p = 0.359$), nor SIDE ($F(1,12) = 1.222$, $p = 0.291$).

Pairwise comparisons indicated reduced peak tibial shock in the trained limb when running at both trained and untrained running speeds after gait retraining (Figure 5.2, *ps* <= 0.002). Quantitatively, a 35-37% reduction in the peak tibial shock after training was demonstrated across running speeds, with Cohen's *d* ranging from 0.78-0.85. Peak tibial shock was also reduced in the untrained limb at both training speed (Figure 5.2, $p = 0.02$) and untrained speeds (Figure 5.2, *p*s = 0.01-0.03). However, the percentage of change and effect sizes in the untrained side were lower, when compared to the trained side (22-30% reduction, Cohen's $d = 0.51$-0.71).

When assessing the amount of reduction in peak tibial shock, no significant SIDE*SPEED interaction was found ($F(2,12) = 2.50$, $p = 0.62$). Pairwise comparison did not reveal significant difference in the reduction in peak tibial shock between limbs (*p*s = 0.31-0.79, Cohen's $d = 0.20$-0.50) or among different running speeds (*p*s = 0.48-0.61, Cohen's $d = 0.06$-0.45).

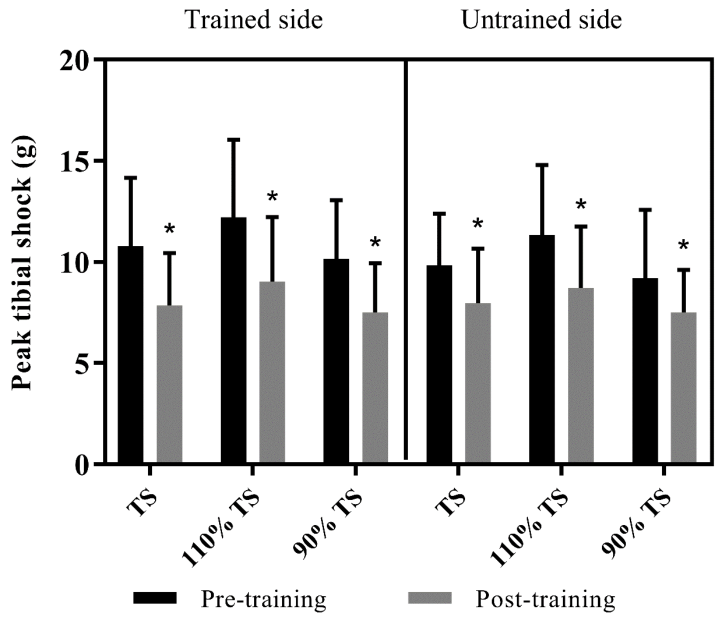

Figure 5.2 Peak tibial shock before and after running gait retraining at three speeds

TS: Training speed

*Significantly reduced compared to pre-training test

5.4 Discussion

The present study examines the effect of gait retraining on the untrained limb when running at untrained speeds. Based on our findings, in spite of the absence of biofeedback on the untrained limb, runners exhibit lower peak tibial shock bilaterally after gait retraining. In addition, participants manage to demonstrate the newly learned running gait within 10% variance of their training speed.

Previous studies reported a reduction of peak tibial shock from 23% to 48% upon completion of the gait retraining (Clansey et al., 2014; Creaby and Franettovich Smith, 2016; Crowell and Davis, 2011). The percentage of reduction of peak tibial shock observed in this study is 37.3% at the training speed, which is similar to previous reports. Runners demonstrated higher amount of reduction compared to the training target value. One possible reason could be that the training target was set lower compared to previous study (Crowell et al., 2010; Crowell and Davis, 2011), and thus it could be easier for the runners to achieve. In addition, runners might perceive the "land softer" instruction to be "as soft as possible", which might also contribute to the further reduction in peak tibial shock. Compared to the trained lower extremity, the untrained limb expressed a 22.7% to 30.1% significant reduction in peak tibial shock, with a medium to large effect sizes (Cohen's d = 0.51-0.71). This result indicates that the untrained lower extremity expressed significant reduction in peak tibial shock even when no feedback was given.

Inconsistent findings about inter-limb motor learning translation in lower limb tasks were reported by past studies. It has been suggested that task with an explicit learning component, such as overcoming an obstacle (van Hedel et al., 2002), or aiming for a target trajectory (Krishnan et al., 2017), might facilitate inter-limb translation. When the participants were not given an explicit goal and were more passively involved during the training, they failed to achieve the expected learning outcome (Houldin et al., 2012). Another factor that may foster inter-limb translation could be utilizing the difference in the function of two brain hemispheres (Springer and Deutsch, 1997), as hypothesized in previous studies (Sainburg, 2002; Stöckel and Wang, 2011), that dynamic feedback provided from the right extremity could enhance the motor learning translation, but not vice versa. Such hypothesis was supported by the result in a previous study (Stöckel and Wang, 2011) as well as the present study. Interestingly, previous study also reported a failure of translation to the right extremity if the dynamic feedback was measured at the left extremity (Stöckel and Wang, 2011). It should be noted that training showed relatively higher effect in the trained limb, compared to the untrained limb in the present study. However, pairwise comparison showed no significant difference in the amount of reduction between trained and untrained limbs. Similar findings were also reported by previous studies (Houldin et al., 2012; Krishnan et al., 2017), which is not a surprise since the biofeedback given were not directly based on the information from the untrained limb. Importantly, the percentage of tibial shock reduction in the untrained limb also reached the training target, which is 20% below the baseline measurement.

Another objective of this study is to test if the trained runners be able to demonstrate the newly learned gait at different speeds. Our findings indicate that the runners were able to retain the newly learned running gait when speed varies within a certain range (i.e. 10% in current study). In the current study, the participants were instructed to focus on an external biofeedback, i.e. peak tibial shock, while no specific instruction about running pattern was given. Previous studies showed that the use of an externally-focused biofeedback might optimize the effect of motor training (Wulf and Lewthwaite, 2016; Wulf and Su, 2007), enhance learning effect, and could favour a translation of the motor learning in different conditions (Chan et al., 2018b). The theory behind was based on the "constrained-action hypothesis" proposed by Sainburg (Sainburg, 2002), that the external focus of attention allows the motor system self-organize naturally. Unlike inter-limb translation, inter-speed translation revealed comparable effect sizes among different testing speed. Post-hoc power analysis revealed a power level at 0.84-0.89, indicating this result is powered. Such result could possible due to the fact that the biofeedback provided directly reflected the outcome of the performance of the trained limb. Hence, it may be easier to achieve a similar effect within the limb across different running speeds.

One of the major limitations of the present study is that the running speed assessed only covered 10% variance, which may limit the generalizability of the findings. The dominant leg of the runners was not recorded and thus future studies will be needed to discuss the direction of inter-limb translation between dominant and non-dominant leg. Post-hoc power analysis showed a power level at 0.56-0.77, indicating the significant reduction in the untrained lower extremity could be underpowered. Based on the effect size from the present study, a larger sample with 24 runners would be needed to power the study. The gender distribution in this study was uneven. Although previous study did not observe a significant difference in peak tibial shock between different genders (Sinclair et al., 2012), female runners were shown at a higher risk of tibial stress fracture than men (Milner et al., 2006). Thus, a gender-balanced sample would be more representative for female runners. This study focused on assessing the motor learning translation of a kinetic parameter, peak tibial shock, before and after gait retraining. Future studies using motion capture to assess training effect to running kinematic parameters, including footstrike pattern and joint angles, would provide a more detailed information towards the training effect on runners.

5.5 Conclusion

In conclusion, gait retraining using biofeedback to reduce peak tibial shock for one side of lower extremity resulted in similar reductions in the untrained limb. Runners were able to maintain the reductions in tibial shock while running at 10% variance of the speed used during gait retraining. The amount of reduction in the peak tibial shock was comparable across both lower limbs and testing speeds. To the best of our knowledge, this is the first study to assess the motor learning translation after running gait retraining. Further analysis would be needed to analyse the motor learning mechanism.

5.6 Project dissemination

Journal publication

Zhang JH, Chan ZYS, Au IPH, An WW, Cheung RTH. (2019) Kinetic control in running retraining: Compare the trained and untrained conditions. *Medicine & Science in Sports & Exercise* (under revision)

Conference proceeding

Zhang JH, Zoe Y.S. Chan, Ivan P.H. Au, Winko W. An, Roy T.H. Cheung. (2018) Can the Newly Learnt Gait Pattern after Running Retraining be Translated to Untrained Conditions? : 1547 Board# 8 May 31, 2018, American Colleague of Sports Medicine (ACSM) Annual Meeting

CHAPTER 6

TRANSLATION OF LEARNING EFFECT GAINED FROM INDOOR-TREADMILL BASED TRAINING PROGRAM TO OUTDOOR EVIRONMENT WITH VARIATIONS IN SLOPES

This chapter is based on the publication on *Gait & Posture* in 2016. The copyright permission has been attached in Appendix I.

6.1 Objectives & Hypotheses

Objectives: This study sought to examine the peak tibial shock during treadmill and overground running on different slopes before and after the current treadmill running gait retraining program.

- **Hypothesis 3.1** There would be training non-respondents, who failed to reduce the peak tibial shock during treadmill level running after gait retraining.
- **Hypothesis 3.2** Runners who were responsive to the gait retraining would maintain the training effect in untrained conditions, including overground and slope running.

6.2 Methods

6.2.1 Participants

Sample size estimation was performed using G*Power (Faul et al., 2007), and the primary variable of interest was peak tibial shock. The effect size of running retraining on peak tibial shock was based on a previously published study (Cheung et al., 2018). With alpha set at 0.05, power at 0.8, and a 10% drop-out rate, 15 participants were adequate to power this study.

Volunteers from local running clubs were invited for a screening test. They were all recreational runners with at least 2-year running experience and a weekly mileage of 10 km or above. All participants were free from any active lower-limb injuries and known musculoskeletal conditions upon enrolment. Verbal and written consent was obtained from each participant before the experiment, which was reviewed and approved by concerning institutional review board.

6.2.2 Screening

One wireless accelerometer (± 24 g, Noraxon, Scottsdale, AZ, USA) was firmly attached on the anterior-medial side of the right distal tibia. The participants were given five minutes to warm up on a treadmill at a self-selected speed, and their preferred running speeds were recorded at the end of the warm-up period (Creaby and Franettovich Smith, 2016). Vertical acceleration was recorded at 500 Hz for one minute after the warm-up period (Cheung et al., 2018), and data were then filtered at 50 Hz using a fourth order Butterworth filter (Zhang et al., 2016). The peak tibial shock in the last ten footfalls was then identified. To avoid the floor effect, only participants with average peak tibial shock greater than 8 g were invited to the pre-training assessment (Crowell and Davis, 2011). Based on a previously published study, a peak tibial shock higher than 8 g was considered higher than the mean value plus one standard deviation in a group of uninjured young adults (Milner et al., 2006). This study screened 18 runners in total to find 15 eligible runners who meet the inclusion criteria (4 females, 11 males; age = 40.9±7.4 years; height = 1.67±0.07 m; weight = 60.5±8.6 kg). They were invited for the following assessments and running retraining.

6.2.3 Pre-training assessment

The pre-training assessment included both indoor treadmill and outdoor overground running evaluations. The testing sequence was randomized, and the participants were running in their usual running shoes in all training and assessment sessions.

During the indoor treadmill running evaluation, all of the participants were asked to run on a treadmill at preferred running speed in three slopes, i.e., level running (LR), 10% uphill running (UR), and 10% downhill running (DR). Peak tibial shock was collected for one minute at each slope using the method identical to the procedures in the screening test (Cheung et al., 2018). In an outdoor overground running evaluation, the UR and DR were conducted on a 20-m concrete surface with 10% elevation and outdoor LR were conducted on a 20-m flat concrete runway as shown in Figure 6.1. The outdoor running speed was monitored using two pairs of photogates set in the middle of the runway. Based on a synchronization signal sent out from the photogates, we identified the acceleration data in the middle of the runway. The participants were instructed to maintain their preferred running speed, and a 5% variance in speed was allowed for each attempt (Kluitenberg et al., 2015). We collected a total of 9 successful strides from each participant for each condition during outdoor running evaluation, and a successful footfall was defined as a trial within target speed range (Sinclair et al., 2013). To match with the number of footfalls in outdoor running, the last 9 footfalls per condition during indoor treadmill running were extracted for further analysis.

Figure 6.1 Outdoor running slope with 10% inclination

6.2.4 Gait retraining

All the included participants then underwent a 2-week 8-session gait retraining program on a treadmill according to a previously established protocol (Crowell and Davis, 2011). In brief, continuous tibial shock data measured at the right distal tibia was provided on a screen at eye level. We provided a line indicating 80% of the average peak tibial shock measured in the pre-training assessment (Cheung et al., 2018), instead of 50% as in the previously protocol (Crowell and Davis, 2011). Participants ran at their preferred speed and were instructed to maintain their peak tibial shock below the threshold. The training time increased from 15 minutes to 30 minutes across the eight sessions, while the feedback was gradually removed in the last four sessions. The participants were allowed to run outside the laboratory training protocol to maintain their weekly mileage. In the meantime, they were also encouraged to maintain the newly learned running gait during their daily running.

6.2.5 Post-training assessment

A post-training assessment was conducted within one week after the completion of the gait retraining (Cheung et al., 2018) and the testing procedure was identical to the pre-training assessment.

6.2.6 Statistical analysis

The Shapiro-Wilk test was used to assess the normality of the data. For normal data, repeated measures ANOVA was used to compare the peak tibial shock under training effect (pre- and post-training test), two running modes (treadmill and overground), and three running slopes (LR, UR, and DR). If indicated, paired t-tests with Bonferroni corrections were performed for pairwise comparisons. Global alpha was set at 0.05.

We also computed reliable change index (RCI) to compare the peak tibial shock difference on an individual level using the following function (Maassen et al., 2009),

$$RCI = \frac{TS_1 - TS_2}{\sqrt{2 \times \left(SD_1 \times \sqrt{1 - r_{xx'}}\right)^2}} ,$$

where TS_1 and TS_2 represent the average peak tibial shock measured in pre- and post-training assessment sessions; SD_1 represents the standard deviation in the pre-training assessment. The reliability coefficient of peak tibial shock ($r_{xx'}$) was set at 0.877, based on previously published data (Raper et al., 2018). An RCI value greater than 1.96 indicates 95% confidence that there is a significant difference in peak tibial shock following gait retraining (Maassen et al., 2009).

6.3 Results

All 15 participants completed the gait retraining and assessment sessions without adverse effect reported. The Shapiro-Wilk test showed that the dataset was normally distributed. Repeated measures ANOVA indicated that there was no interaction effect between running mode (i.e., treadmill vs. overground) and slopes. While peak tibial shock was significantly affected by running slopes ($F = 4.40$, $p = 0.041$), it remained comparable between running modes ($F = 3.242$, $p = 0.093$).

The comparison between pre- and post-training assessments showed that the 15 participants significantly reduced their peak tibial shock by 28.5% following gait retraining ($p < 0.05$, Cohen's d = 1.65). However, on an individual level, three participants exhibited less than 4.29% reduction in peak tibial shock during treadmill running (Figure 6.2, RCIs < 1.44). Thus, those three participants were regarded as non-respondents and they were excluded from further analysis assessing both overground and slope running performance.

The averaged peak tibial shock from the remaining 12 respondents in each running condition are presented in Figure 6.3. Statistically, the effect of gait retraining, running mode (treadmill vs. overground), and running slope significantly interacted with each other ($F= 4.31$; $p = 0.026$). Training effect significantly interacted with running mode ($F = 11.45$, $p = 0.006$) as well as running slope ($F = 4.42$; $p = 0.024$). However, there was no significant interaction between running mode and slope ($F = 0.78$; $p = 0.47$). Peak tibial shock was significantly affected by gait retraining ($F = 28.48$; $p < 0.05$), but it was comparable between treadmill and overground running ($F = 0.028$; $p = 0.87$), and across the three slopes ($F = 2.51$; $p = 0.11$). Pairwise comparison indicated that during treadmill running, the 12 respondents were able to reduce their peak tibial shock in UR ($p = 0.001$, Cohen's d = 0.91) and DR ($p < 0.05$; Cohen's d = 1.29) conditions. Moreover, they managed to reduce the peak tibial shock during outdoor level running ($p = 0.014$, Cohen's d = 0.85). However, they failed to translate the learning effect during outdoor UR ($p = 0.054$; Cohen's d = 0.62) and DR ($p = 0.12$; Cohen's d = 0.48).

Table 6.1 Interaction of TRAINING, RUNNING MODE, and SLOPE effect on peak tibial shock

	F	p
Training	12.18	0.004
Running mode	0.16	0.695
Slope	4.46	0.038
Training * Running mode	11.45	0.006
Training * Slope	4.42	0.024
Running mode * Slope	0.78	0.47
Training * Running mode * Slope	4.31	0.026

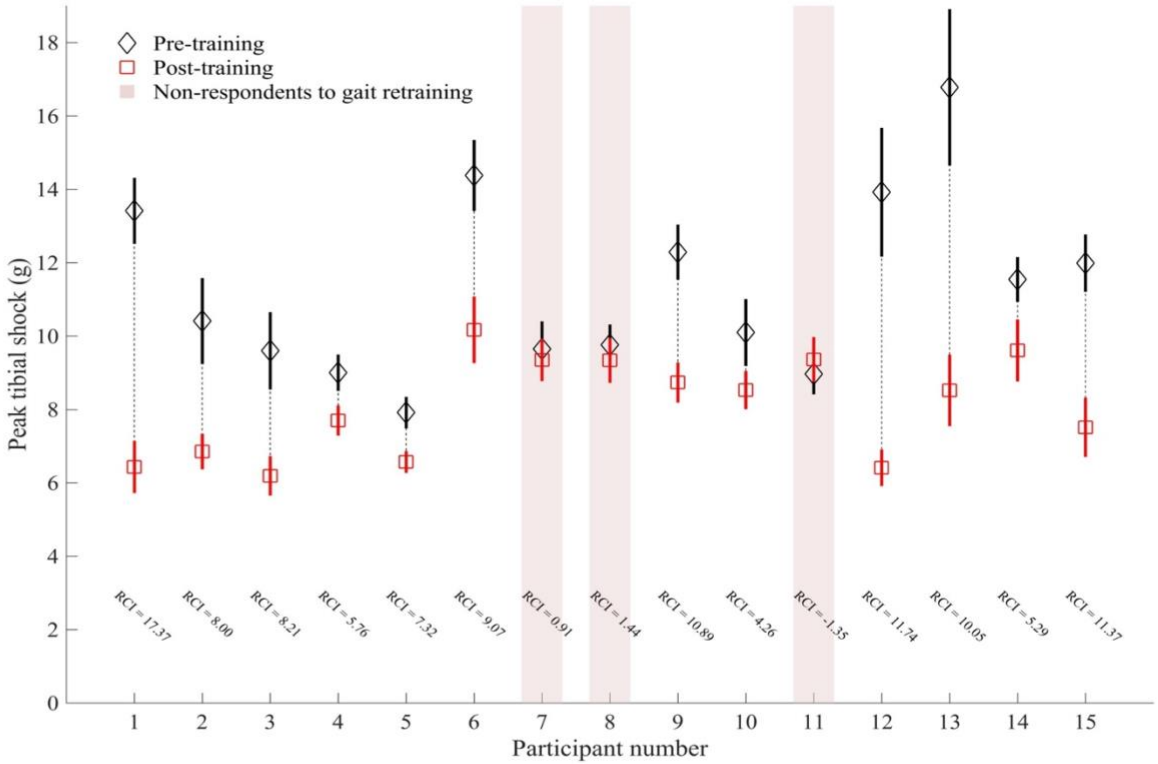

Figure 6.2 Pre- and post-training comparison of peak tibial shock during treadmill level running conditions

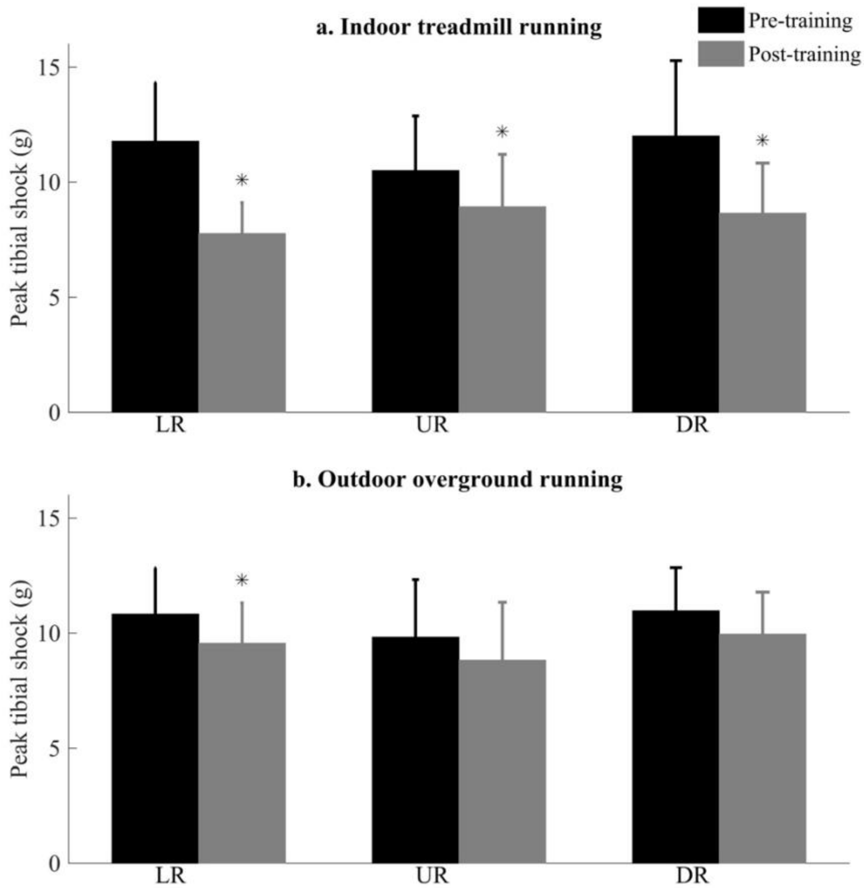

Figure 6.3 Comparison of peak tibial shock before and after gait retraining during treadmill and overground running in the three slopes

* Significant reduction compared to pre-training assessment

6.4 Discussion

This study aimed to assess the translation of the training effect from a treadmill-based gait retraining program to overground, and to different running slopes. Runners experienced impact loading reduction in level treadmill running, and they were able to translate the effect to treadmill and slope running and outdoor level running. However, such skill was not fully translated when they were running on outdoor slopes.

In general, the gait retraining protocol used in this study reduced the peak tibial shock by 28.5% in the current participant sample, regardless of respondents and non-respondents. Such reduction fell within the range reported by previous gait retraining studies, which showed a 10.0% to 44.7% reduction in peak tibial shock following training (Cheung et al., 2018; Crowell et al., 2010; Wood and Kipp, 2014). The variation in the training effect could be due to different training targets (ranging from 10% to 50% lower than the baseline value) (Cheung et al., 2018; Clansey et al., 2014; Crowell and Davis, 2011; Wood and Kipp, 2014), and training intensity (from a single session 10-minute feedback training to a structured 8-session program) (Creaby and Franettovich Smith, 2016; Crowell and Davis, 2011; Wood and Kipp, 2014).

However, when the training effect was examined on an individual level, our results indicated an 80% training-response rate to the protocol used in this study. Crowell *et al.* reported a similar training-responsive rate in their gait retraining (Crowell et al., 2010). From a motor learning perspective, real-time visual feedback indicating the effect of movement would attract an external focus of attention (Shea and Wulf, 1999), decrease the cognitive load (Wulf and Shea, 2002), and thus was considered beneficial to the learning process (Sigrist et al., 2013). A faded feedback design was shown to be effective to avoid feedback dependency (Crowell and Davis, 2011). However, the optimal fading rate of the feedback was yet unknown. Regarding the varied learning capacity of individuals, the fading procedure adopted in this study was possibly not optimized for every participant. Recent studies using performance-based fading feedback showed better learning results compared to training courses using constant feedback fading rate for all learners (Huegel and O'Malley, 2010). Therefore, in future gait retraining studies, a more flexible feedback protocol should be considered for better individualized outcomes.

Following a course of gait retraining on a level treadmill, runners appeared to exhibit softer footfalls during treadmill slope running. However, the effect of training interacted significantly with running slope. Such interaction could also be shown from the Cohen's *d* value calculated based on the peak tibial shock collected in pre- and post-training assessments among different slopes. The effect size of training was relatively larger during DR than UR, which could be due to the relatively lower baseline peak tibial shock values during UR (Zhang et al., 2016), leading to a possible floor effect (Crowell and Davis, 2011). The reason for a reduced impact loading in UR could be due to a change in the landing pattern (Vernillo et al., 2016), or reduced centre of mass displacement (An et al., 2015; Firminger et al., 2018). As we did not collect motion data in this experiment, further studies would be needed to assess the kinematics changes following gait retraining.

The 12 training-responsive participants significantly reduced their peak tibial shock by 11.7% during overground level running. However, a significant interaction between the training effect and running mode (treadmill vs. overground) was demonstrated, which could be explained by the reduced effect size of training during overground level running (Cohen's $d = 0.85$). Compared to the present study, previous studies (Clansey et al., 2014; Crowell and Davis, 2011) reported larger effect (Cohen's $d = 1.5$) and greater reduction (31-48%) during overground running after treadmill-based gait retraining. Such discrepancy could be a result of a more strict training target (i.e., 50% off from the pre-training value) adopted in previous studies (Clansey et al., 2014; Crowell and Davis, 2011). In contrast to our original hypothesis, the participants responding to the gait retraining were only able to demonstrate a lower peak tibial shock during outdoor level running, but not on slopes. Post-hoc power analysis showed that the findings were sufficiently powered in the overground level running condition (Power = 0.86), but not in overground slope running conditions (Power = 0.47-0.65). A sample size estimation based on the current dataset showed a sample of 29 participants would be sufficient to power this investigation.

Running overground on slopes requires motor translation at two levels, from treadmill to overground, and from level ground to slopes. The increased task complexity could challenge the training effect translation. A previous gait retraining study reported that the peak tibial shock showed an increasing trend at the 3-month follow-up (Crowell and Davis, 2011). Combined with the results from the current study, changes to the current running retraining protocol may be needed to improve the learning effect. Previous motor learning studies put forward the importance of variation in training as well as training intensity (Bonney et al., 2017; Breslin et al., 2012). It has been shown that training variation is important for skill retention and learning effect translation (Breslin et al., 2012). However, the current gait retraining protocol may only provide the participants with sufficient training intensity but not variation. Whether or not a running retraining protocol with variation, such as running speeds and slopes, could lead to a better learning effect are underexplored. Further studies will be needed to assess the effect of gait retraining with more diversified training conditions.

The limitations should be considered when interpreting the findings of the current study. Since this study mainly focused on the running kinetics, joint kinematics data were not assessed. Further studies assessing the running kinematics would be warranted. The participants' extra running mileage outside the training protocol was not controlled in this study, which could affect the training effect and the translation of the learning effect. In this study, the overground running tests were conducted on a concrete surface, which may limit the generalizability of the findings. The lack of significant difference in the peak tibial shock in outdoor slope running may be due to an insufficient number of subjects.

6.5 Conclusion

After completion of an indoor-treadmill based gait retraining program, 80% of the participants managed to reduce their peak tibial shock in treadmill level and slope running conditions. The training-responsive runners managed to reduce their peak tibial shock during outdoor level running, but not during outdoor slope running. In view of our findings, refinement of the training protocol used in this study may be needed to improve the effects of the gait retraining and increase the ratio of training-responsive runners.

6.6 Project dissemination

Journal publication

Zhang JH, Chan ZYS, Au IPH, An WW, Cheung RTH. (2019) Can runners maintain the newly learned gait pattern outside laboratory environment following gait retraining? *Gait & Posture*, 69: 8-11

Conference proceeding

Zhang JH, Chan ZYS, Au IPH, An WW, Cheung RTH. (2018) Transfer of the learning effect in outdoor conditions with varied surface inclinations upon completion of an indoor gait retraining program, 11^{th} Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Oral Presentation Award)**

Zhang JH, An WW, Au IPH, Chan ZYS, Cheung RTH (2016) Kinetics control in runners at different running speeds and slopes after completion of a gait retraining program. The 5th HKASMSS Student Conference on Sports Medicine, Rehabilitation and Exercise Science 2016, 26 November 2016, Hong Kong SAR

CHAPTER 7
MOTOR STRATEGIES AND LEANRING EFFECT TRANSLATION AFTER COMPLETION OF A CURRENT RUNNING GAIT RETRAINING PROGRAM

7.1 Objectives & Hypotheses

Objectives: This study sought to identify motor strategies adopted by the runners after the current treadmill running gait retraining program. This study did individual analysis to assess the how these changes would affect the motor learning translation to varied running speeds and slopes.

- **Hypothesis 4.1** Runners showed different strategies after the training, including changes in stride length and footstrike angle.
- **Hypothesis 4.2** Runners who adopted multiple strategies showed better training effect translation when running at varied speeds and slopes.

7.2 Methods

7.2.1 Participants

Five male runners (age = 32.4±9.1 yo, height = 1.74±0.07 m, weight = 67.0±6.0 kg) were recruited from local running clubs. They were recreational runners with more than 2-year running experience, and a self-reported weekly distance greater than 10 km (Zhang et al., 2016). All participants were free from any active injury upon enrolment. Verbal and written consents were obtained from all the participants prior to the experiment, which was reviewed and approved by the institutional review board of the Hong Kong Polytechnic University.

7.2.2 Experiment procedures

We determined the preferred running speed (PRS) of each participant was recorded using a 5-minute self-paced treadmill running protocol (Chen et al., 2016) and individualized PRS was used as the training speed for each participant. The participants underwent an established training protocol identical to the one described in Chapter 5.

A pre-training assessment was conducted with five running conditions with variance in running slopes and running speeds. The five trials were conducted in a random order. Participants were asked to run on a treadmill during level running (LR), 10% uphill running (UR), and -10% downhill running (DR) conditions. During LR, all participants were asked to run at three different speeds, including PRS, 110% PRS, and 90% PRS. The participants were asked to run at PRS during UR and DR conditions. Upon the completion of the gait retraining program, a post-training assessment was conducted which was identical with the pre-training assessment.

7.2.3 Data collection

One wireless accelerometer (± 24g, Noraxon, Scottsdale, AZ, USA) were firmly affixed onto the anterior-medial surface of the right distal tibia with the z-axis alongside the longitudinal axis of the tibia (Crowell and Davis, 2011). During each running trial, participants were asked to run for three minutes (Cheung et al., 2018) and the vertical acceleration data were collected at 500 Hz. Joint kinematics were collected at 100 Hz using a set of lower limb inertial measurement units (Noraxon, Arizona, USA). The acceleration data and kinematics data were then filtered at 50 Hz and 8 Hz using a fourth order Butterworth filter respectively (Zhang et al., 2016). The peak tibial shock, stride length, and ankle joint angle in the last 10 footfalls were then identified and used for comparison.

7.2.4 Statistical analysis

The statistical analysis used a single-subject analysis method employed by Crowell et al. (Crowell et al., 2010). In a single-subject analysis, the data from a single participant were treated as if they were data from a group of subjects in an experiment (Bates, 1996). Each trial in a single-subject analysis was considered as an independent sample (Crowell et al., 2010). Therefore, independent t-tests were conducted to compare the peak tibial shock, stride length, and ankle dorsiflexion angle at initial contact between pre- and post-training assessments. Global alpha level was set at 0.05.

7.3 Results

Single subject analysis revealed that four of the participants (Sub #1-4) significantly reduced their PTS after training in during level running condition at training speed (*p*s<0.05; Cohen's *d*s>1.14). These four training respondents managed to demonstrate the newly learned gait in most of the untrained conditions. Two strategies, including shortening stride length and reducing ankle dorsiflexion ankle at initial contact, were observed in all respondents. Participants adopting both strategies (Sub #2 and #4) demonstrated consistent learning effect translation in different running conditions. However, Sub #3 failed to reduce the PTS significantly during uphill running test (p = 0.93; Cohen's d = 0.04). Moreover, a participant (Sub #1) who adopted a single strategy failed to translate the learning effect when running at a slower speed (Table 7.1).

Another participant (Sub #5) did not significantly reduce PTS after training. This runner demonstrated a reduction of stride length but increased ankle dorsiflexion angle at initial contact after training (Table 7.1). The result from the current study provided preliminary information regarding the kinematics strategies after completion of a kinetic-based gait retraining.

Table 7.1: Individual data showing the difference^ in peak tibial shock (PTS), stride length (SL), and initial ankle dorsiflexion angle (AnkAng) before and after training during five testing conditions

	LR & PRS			LR & 110%PRS			LR & 90%PRS			UR & PRS			DR & PRS		
Sub	PTS (g)	SL (m)	AnkAng# (°)	PTS (g)	SL (m)	AnkAng (°)	PTS (g)	SL (m)	AnkAng (°)	PTS (g)	SL (m)	AnkAng (°)	PTS (g)	SL (m)	AnkAng (°)
1	-1.98*	-0.02*	-6.25	-1.69*	-0.03*	5.65*	0.20	-0.06*	-2.31	-2.51*	-0.05*	6.28	-2.71*	-0.16*	-3.12
2	-3.32*	-0.02	-3.77*	-3.58*	-0.10*	-4.90*	-1.88*	-0.03*	-6.17*	-1.79*	0.03*	-0.65	-3.02*	0.09*	-7.12*
3	-1.32*	-0.09*	-0.06	-2.75*	-0.09*	-4.37*	-2.05*	-0.09*	-3.53*	-0.12	-0.09*	-2.09*	-2.41*	-0.10*	-5.68*
4	-3.59*	-0.38*	-20.35*	-3.50*	-0.44*	-9.59*	-3.05*	-0.30*	-18.61*	-2.61*	-0.26*	-4.19*	-1.30*	-0.16*	-25.75*
5	2.36*	-0.10*	8.37*	1.15*	-0.04*	4.42	0.10	-0.05*	-0.19	-0.56*	-0.07*	4.59*	-0.38	-0.19*	-15.65*

^ Data shown as value measured in post-training test minus that measured in pre-training test

Negative value indicates a less dorsiflexed ankle during initial contact during post-training test

*$p < 0.05$

7.4 Discussion

This subgroup analysis identified two motor strategies adopted by the participants following gait retraining, including adjusting stride length and footstrike pattern. The current results suggested that runners who adopted a combination of the two strategies tended to perform better in motor learning translation than runners who only manage to adopt single motor strategy.

Our findings indicated that 4 out of the 5 runners who completed the current gait retraining protocol reduced PTS in the trained condition. Such respondent rate was comparable with previous findings (Crowell et al., 2010; Zhang et al., 2019). The training non-respondent (Sub #5) experienced higher PTS after training, which could be explained by the increased ankle dorsiflexion angle at initial contact. Previous studies suggested that an increased ankle dorsiflexion at initial contact could indicate a rearfoot strike landing pattern (Lieberman et al., 2010), which has been shown to related to an increased lower extremity loading (An et al., 2015; Lieberman et al., 2010) and PTS.

Previous studies showed that runners reduced patellofemoral joint loading when they were instructed to shorten their stride length (Heiderscheit et al., 2011; Lenhart et al., 2014; Willson et al., 2015), or to transit to a non-rearfoot strike landing pattern (Willson et al., 2015). Our current studies suggested that runners managed to adopt these two motor strategies even without an explicit instruction given. This could be a result of the design of the current training protocol. It has been suggested that the learning outcome could be optimized when the real-time feedback directed the focus of attention externally to the result of the action, instead internally to the body that actually makes the action (Wulf and Lewthwaite, 2016).

Another focus of this study was to assess the learning translation from trained to untrained conditions. Our data showed that two of the runners (Sub #2 and #4) managed to combine the two motor strategies and maintained a consistently reduced PTS in all untrained conditions. Meanwhile, Sub #1, who only shortened the stride length, failed to reduce the PTS during treadmill level running condition at 90% of the preferred running speed. On the other hand, Sub #3 did not manage to lower PTS during uphill running at the usual running speed. One possible reason is due to a floor effect, i.e., PTS may be too low for further reduction when running at a slower speed (Fortune et al., 2014), or on an inclined slope (Zhang et al., 2016).

From a motor learning perspective, another possible reason for the unsuccessful motor learning translation to some untrained conditions could be due to a "freeze out" effect (Bernstein, 1966). Described by Bernstein, learners might experience a "freeze out" phase at the early stage of motor learning and used a single degree of freedom to achieve the learning target. In other words, the learner may express a fixed joint angle or an increased whole body stiffness (Vereijken et al., 1992). After the "freeze out", learners would manage to release some degrees of freedom to achieve the motor target, which means an increased joint movement (Vereijken et al., 1992), or recruitment of cooperation with different body segments (Domkin et al., 2002). In our current dataset, we noticed that Sub #1 managed to reduce the stride length in all five running conditions, but we did not observe a decreased ankle dorsiflexion angle in this participant. Combined with Bernstein's theory, we therefore suggested that Sub #1 could still be in the "freeze out" phase after completion of the 8-session gait retraining.

The small scale sample in the current dataset could limit the impact of this investigation. Post-hoc analysis based on the current study suggested that a sample of 16 runners would be able to power this investigation. Another limitation of the current study is that the learning process of each participant was not assessed. Further studies to assess the duration of "freeze out" could provide insights for the design of a gait retraining protocol. Another possibility proposed by Bernstein was that the runners could attain redundant motor strategies after training (Bernstein, 1966; Latash et al., 2001). However, since the current study did not look into the joint kinematics in hip and knee, a study reporting lower limb joint kinematics data would be needed to identify other potential motor strategies adopted by the runners.

7.5 Conclusion

The result from the current study showed that 80% of the participants were responsive to the current gait retraining protocol. Control of impact loading with multiple strategies might potentially benefit the motor learning of gait retraining.

7.6 Project dissemination

Journal publication

Zhang JH, Chan ZYS, Cheung RTH. (2019) Kinetic and kinematic analysis of the learning effect of a laboratory-based gait retraining in untrained running conditions. *Journal of Science and Medicine in Sport* (in preparation)

Conference proceeding

Zhang JH, Chan ZYS, Cheung RTH. (2019) Motor strategies and learning effect translation in an established running retraining program, XXVII Congress of the International Society of Biomechanics, 31 Jul – 4 Aug, Calgary, Canada **(Winner of Congress Travel Grant)**

CHAPTER 8
CONCLUSION

8.1 Summary

Most current gait retraining protocols adopt a laboratory setting with running speed and slope controlled, while most of the runners practice outdoor in a natural running environment. Natural running conditions involve a lot of variations in the running surface, speeds, slopes, etc. Thus, the overall mission of this thesis is to examine the motor learning translation between a natural and a laboratory running environment following gait retraining.

To measure the running kinetics in an outdoor environment, this thesis firstly evaluated the association between peak tibial shock and vertical loading rate (Chapter 4). Based on the strong intra-subject association between these two parameters, series of studies (Chapter 5-7) were conducted to assess motor learning translation of an established gait retraining protocol from four perspectives, including 1) inter-limb translation; 2) inter-speed translation; 3) inter-slope translation; and 4) treadmill-overground translation. The results and conclusions of each study have been addressed in respective chapters, and they are summarized here:

Chapter 4 Based on the results of the study, wireless accelerometers can be used to estimate VLRs within an individual in an outdoor running environment. Due to high inter-subject variance, comparison of PTA between subjects should be made with caution.

Chapter 5 Gait retraining using biofeedback to reduce peak tibial shock for one side of lower extremity resulted in similar reductions in the untrained limb. Runners were able to maintain the reductions in the tibial shock while running at 10% variance of the speed used during gait retraining. The amount of reduction in the peak tibial shock was comparable across both lower limbs and testing speeds. To our best knowledge, this is the first study to assess the motor learning translation after running gait retraining. Further analysis would be needed to analyse the motor learning mechanism.

Chapter 6 After completion of an indoor-treadmill based gait retraining program, 80% of the participants managed to reduce their peak tibial shock in treadmill level running and slope running conditions. The training respondents managed to reduce their peak tibial shock during outdoor level running, but not during outdoor slope running. In view of our findings, refinement of the current training protocol is needed to improve the responsiveness, as well as promote a better learning effect translation.

Chapter 7 The results from the current study showed that 80% of the participants were responsive to the current gait retraining protocol. Control of impact loading with multiple strategies might potentially benefit the motor learning of gait retraining.

8.2 Future work

With a 20% of non-responsive rate reported in this PhD project, an individualized gait retraining protocol would be beneficial, especially to those non-respondents. We therefore suggest optimizing the current training protocol in future studies. The aim of gait retraining could be summarized as to reduce injury risk, and in the meantime to avoid penalty in running economy. Thus, suggestions for future study could be divided into two categories, including 1) to maximize the training effect, which is to increase the amount of reduction in peak tibial shock in the training protocol used in this thesis; and 2) to reduce the physiological demand following gait retraining.

To optimize the training effect, two variables in a training protocol could be adjusted, including total training time and feedback fading rate. Previous studies using multi-session gait retraining protocols (Clansey et al., 2014; Crowell and Davis, 2011; Zhang et al., 2019) reported greater training effect than the single-session training (Creaby and Franettovich Smith, 2016; Townshend et al., 2017; Wood and Kipp, 2014). These results indicated the importance of total training time in improving the effect. The fading feedback design has been shown to be beneficial to avoid feedback reliance (Winstein, 1991), but the learning rate could be different across individuals. Previous motor learning study proposed a training protocol design with progressive feedback fading rate, that the feedback would be gradually removed when the learner performed better (Huegel and O'Malley, 2009). Such protocol was shown with better motor learning outcome than a training protocol using constant feedback fading rate (Huegel and O'Malley, 2009).

It would be interesting to implement a similar design into a gait retraining protocol, with adjustable total training time and fading rate. Future studies to evaluate whether such individualized protocol could induce a larger training effect are therefore warranted.

Although the main aim of running gait retraining is to reduce injury risk, we also want to avoid any physiological penalty caused by the training. A previous study reported an increased oxygen consumption after a single-session of gait retraining (Townshend et al., 2017). However, such additional physiological cost could be diminished by increasing the total training time to 3 weeks (Clansey et al., 2014). It remains unclear how long it takes the runners to adopt the modified running pattern to maintain a comparable oxygen consumption level. With this question been addressed, further studies could explore the potentiality of including running economy as one of the determinants in the training protocol design.

SECTION II
EXPLORATORY STUDIES IN GAIT MODIFICATION

Every once in a while, a new technology, an old problem, and a big idea turn into an innovation

-- Dean Kamen

The second section describes four studies investigating exploratory ideas in the areas of gait modification, injury prevention, and stroke rehabilitation. Through these studies, we evaluated an innovative running shoe design (Chapter 9) and explored potential training strategies in distance running (Chapter 10). Moreover, we assessed the application of an artificial neural network model in running (Chapter 11) and reported some preliminary results on the development of a wearable exoskeleton for stroke patients (Chapter 12). Because these studies were relatively independent from each other, the background information was given in each individual chapter.

CHAPTER 9

ASSESSMENT OF A NEW FOOTWEAR TECHNOLOGY WHICH CLAIMS TO REDUCE ENERGY LOSS AND CHANGE FOOTSTRIKE PATTERN

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9.1 Introduction

Running has a high incidence of injuries (Gent et al., 2007), and it has been reported that an increased impact force and vertical loading rates were associated with some certain injuries, such as tibial stress fracture (Pohl et al., 2008; Worp et al., 2016; Zadpoor and Nikooyan, 2011). Barefoot running has been proposed as a means to reduce impact forces and vertical loading rates, which is based on a potential instinctively landing pattern transition from rearfoot strike (RFS) to forefoot (FFS) or midfoot strike (MFS) (An et al., 2015; Cheung and Rainbow, 2014). Although barefoot running may not directly lead to reduced loading rates (Tam et al., 2016), it has increased in popularity among runners. Despite the potential benefit of barefoot running, most runners still choose to wear shoes to protect the plantar surface (Altman and Davis, 2015). In view of this demand in the market, many running shoe companies have developed minimalist running shoes, which are characterized as light-weighted, with high flexibility, low heel to toe drop, low stack height, and lack of motion control or stability devices (Esculier et al., 2015).

Running in minimalist shoes may simulate barefoot running biomechanics (Hollander et al., 2015; Squadrone and Gallozzi, 2009), which may lead to landing pattern shift and a decreased vertical loading rate. A lower heel to toe drop may lead to a transition in landing pattern from RFS to MFS or FFS (Horvais and Samozino, 2013). In addition, running in minimalist shoes may promote performance by utilizing less amount of oxygen than shod running (Cheung and Ngai, 2015; Franz et al., 2012). Better running performance could be a result of lower shoe mass, which was found to correlate with the cost of running (Franz et al., 2012; Lussiana et al., 2013).

To promote running performance, some footwear technologies have recently been introduced into running shoes (J. Sinclair et al., 2016). Among them, a newly developed design, called 'actuator lugs' which embedded under minimalist shoes (Newton Running Lab®, Boulder, CO, USA), claims for better shock absorption and energy return (Abshire, 2015). In this "actuator lugs" design, five actuator lugs were embedded under the forefoot area (Figure 9.1). According to its patent, the actuator lugs will be compressed into a recess during impact for storing energy; and the stored energy will be returned during the propulsion (Abshire, 2015). A previous study reported an improvement in running economy in highly-trained runners when running in this new shoe model, compared with running in a same shoe model without lugs (Moran and Greer, 2013). However, the biomechanical parameters during running in this energy return shoes have not been assessed. According to the mass-spring model (Farley and González, 1996; McMahon and Cheng, 1990), the energy exchange during running can be graphically represented by a hysteresis loop and the area of the loop indicates the amount of energy loss (Hunter, 2003). As running with RFS and non-RFS differ in terms of the effective mass during impact (Lieberman et al., 2010), the difference in the energy loss between shod running and running in minimalist shoes may be mostly contributed by the initial vertical body stiffness (Hunter, 2003).

The present study sought to compare the landing pattern, vertical loading rates, energy loss, and initial vertical body stiffness in a group of habitual shod runners who ran in traditional running shoes and the minimalist shoes with actuator lug platform. We hypothesized that the newly footwear design would promote non-RFS landing. With such landing pattern switch, the vertical loading rates were expected to be reduced. We also hypothesized that running in minimalist shoes with lug platform would decrease energy loss by lowering the initial vertical body stiffness, when compared with traditional running shoes.

9.2 Methods

9.2.1 Participants

A prior sample size estimation was conducted based on the data from previous studies (Willy and Davis, 2014), with α setting at 0.05, β at 0.8. Fifteen shod runners (9 males and 6 females; age=21.8 ± 4.0 years; body height=1.72 ± 0.74 m; body mass=63.7 ± 11.3 kg), who habitually landed with RFS and free from any active lower-extremity injuries, were recruited from local running clubs. All the participants were recreational runners who ran more than 10 km per week for the past six months and had not experienced any type of minimalist shoes or barefoot running prior to the investigation. Participants were also required to be familiar with treadmill running, with at least 20-minute treadmill running per week for the past three months. (Rixe et al., 2012). Verbal and written consent were obtained from all the participants prior to the experiment, which was reviewed and approved by the concerning institutional review board.

9.2.2 Experiment procedures

Participants were asked to run on an instrumented treadmill (AMTI®, Watertown, MA, USA) at 8.0 $km \cdot h^{-1}$ in two footwear conditions: 1) participant's usual traditional running shoes (shoe mass = 10.44 ± 1.99 oz, stack height = 28.88 ± 4.36 mm, heel to toe drop = 10.71 ± 1.70 mm); and 2) a minimalist shoe model with lug platform (MV2, Newton Running Lab®, Boulder, CO, USA) (shoe mass = 5.8 oz (size 9), stack height = 17 mm, heel to toe drop = 0 mm, with five actuator lugs embedded below the forefoot in the outsole (Figure 9.1), without any instruction. The two footwear conditions were tested in a randomized sequence, with at least 48 hours between each test (Fellin and Davis, 2009). The subjects were given 10 minutes to accommodate treadmill running (Horvais and Samozino, 2013) and then the data were collected for one minute.

Figure 9.1 Outsole of the Newton MV2, displaying the actuator lugs

9.2.3 Data collection

Reflective markers were firmly affixed on the shoes according to a model described previously (Altman and Davis, 2012) and Vicon® motion analysis system (Oxford, Metrics, Oxford, UK) was used to capture the trajectory of the markers at 200 Hz and lowpass filtered at 8 Hz during running. For the kinetics data, vertical ground reaction force (VGRF) was recorded at 1,000 Hz, filtered at 50 Hz with a fourth order Butterworth lowpass filter. A cutoff threshold at 20 N was used to identify the initial contact (McCallion et al., 2014). We identified the last consecutive 20 steps in the 1-minute running, with 10 steps from each side. The GRF data were then normalized by body weight, and the following independent variables in the 20 steps were calculated.

Footstrike angle

The footstrike angle (FSA) at the first contact of each stance was subtracted by the angle during static standing calibration (Altman and Davis, 2012). Landing patterns were classified according to established criteria i.e. FFS < -1.6˚ < MFS < 8˚ <RFS (Altman and Davis, 2012).

Vertical loading rates

Average (VALR) and instantaneous vertical loading rate (VILR) were obtained by the method previously described (Milner et al., 2006), that VALR was the slope of the line through the 20% point and the 80% point of the vertical impact peak and VILR was the maximum slope of the vertical ground reaction force curve between successive data points in the same region. In case of an absence of the vertical impact peak, VALR and VILR were calculated according to the method described by Blackmore *et al*. (Blackmore et al., 2016). A set value of 13% stance was used as a surrogate for time to vertical impact peak.

Initial vertical body stiffness and energy loss

The vertical displacement of the centre of mass (COM) was calculated using a double integration technique to the VGRF (Hunter, 2003). The acceleration of the COM was calculated by subtracting the participants' body weight from the net VGRF, and then dividing it by the participants' body mass. The VGRF versus COM displacement formed a hysteresis loop. The energy loss was then calculated as the difference between the negative COM work and the positive COM work (Dalleau et al., 1998), normalized by body mass. The energy loss could also be expressed as the area of the hysteresis loop.

The vertical stiffness during initial contact was calculated according to the equation

$$\text{vGRF}(t) = -k(t) \times x$$

where t is the time, $x(t)$ is the displacement of COM, and $k(t)$ is the vertical stiffness, and initial contact was defined as the time from contact to the impact peak (Samaan et al., 2014). For the trials without an impact peak, similarly, a set value of 13% stance was used as a surrogate for time to vertical impact peak (Blackmore et al., 2016).

9.2.4 Statistical analysis

All the data were processed using SPSS.21® statistics software of package (Chicago, IL, USA). Global alpha was set at 0.05. Paired-t tests were used to compare the differences in the FSA, vertical loading rates (VALR and VILR), initial vertical body stiffness, and energy loss between two footwear conditions. In order to avoid overreliance to statistical tests, Cohen's d was calculated to evaluate the effect size between conditions. Post-hoc power analysis was conducted if no significant difference was detected between conditions.

9.3 Results

Please see Table 9.1 for summary of results. The FSA decreased significantly when running in minimalist shoe model with actuator lugs (P = 0.003, Cohen's d = 0.918, Table 9.1). However, the mean value was still within a RFS range (FSA = 13.02 ± 2.76° in usual shoes; 9.36 ± 4,64° in minimalist shoes).

Kinetically, we did not find any significant differences in the VALR (P = 0.191, Cohen's d = 0.355) and VILR (P = 0.258, Cohen's d = 0.304) between two footwear conditions (Table 9.1). Post hoc power analysis showed the type II error β = 0.632 for VALR, and β = 0.700 for VILR. The hysteresis loops in two footwear conditions are shown in Figure 9.2. We found greater initial vertical stiffness (P = 0.032, Cohen's d = 0.671, Table 1) and energy loss (P = 0.044, Cohen's d = 0.578, Table 9.1), with medium effect size, while running with the new shoe model.

Table 9.1 Comparison of biomechanical parameters between two footwear conditions (n = 15)

	Traditional running shoes	Minimalist running shoes with lug platform	p-value	Cohen's d
Foot strike angle (°)	13.02 ± 2.76	9.36 ± 4.64	0.003*	0.918
Average vertical loading rate (BW s^{-1})	74.32 ± 18.72	80.99 ± 21.70	0.191	0.355
Instantaneous vertical loading rate (BW s^{-1})	90.60 ± 20.09	96.86 ± 25.64	0.258	0.304
Energy Loss (J kg^{-1})	0.221 ± 0.097	0.258 ± 0.116	0.044*	0.578
Initial vertical stiffness (kN m^{-1})	53.69 ± 11.44	62.19 ± 10.71	0.032*	0.671

*$p < 0.05$

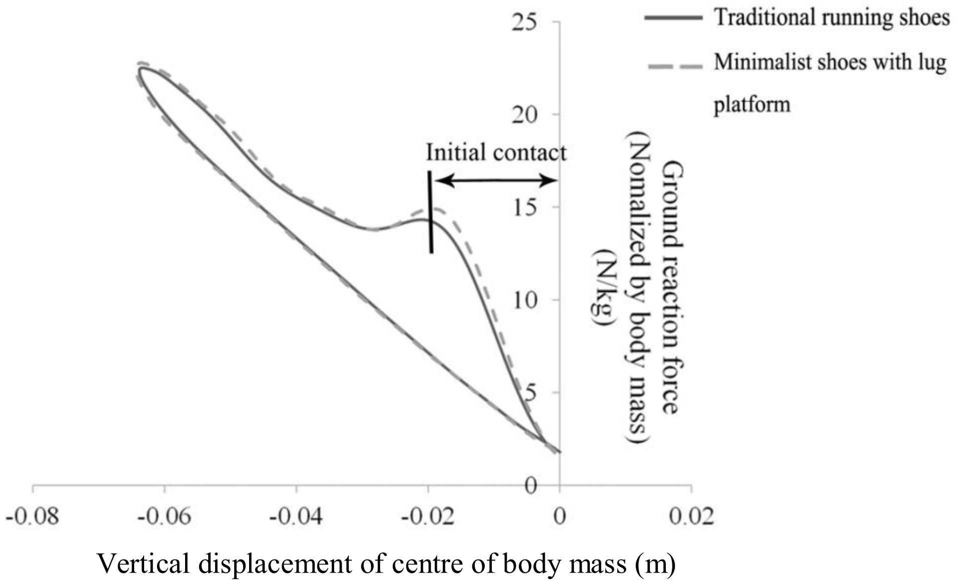

Figure 9.2 Hysteresis loop while running with traditional running shoes and minimalist shoes with lug platform (n = 15)

9.4 Discussion

This study examined the immediate effects of a newly developed footwear model on the landing pattern, vertical loading rates, initial vertical body stiffness, and energy loss, in a group of habitual shod runners. We found that the minimalist shoes with actuator lugs tended to reduce the FSA, but it did not lead to a landing pattern switch or lower the vertical loading rates. Interestingly, the new shoe model did not enhance energy exchange. Instead, it induced a greater energy loss than the traditional running shoes, which could be explained by a higher initial vertical body stiffness.

In spite of a lower FSA, most of the runners maintained RFS when running in the minimalist shoes with actuator lugs. Such findings were comparable with some previous studies investigating the effects of minimalist shoes in habitual shod runners (An et al., 2015; Moore et al., 2015; Ryan et al., 2013; Squadrone and Gallozzi, 2009). On the contrary, there were few studies reporting conflicting findings (Bonacci et al., 2013; Willson et al., 2014; Willy and Davis, 2014). Such discrepancy may be due to the wide spectrum of minimalist shoe properties (Esculier et al., 2015) and difference in the adaptation time allowed for novice footwear condition (Cheung and Rainbow, 2014; Moore et al., 2015; Ryan et al., 2013).

Our findings on the impact loading could be explained by the inconsistent landing pattern transition in habitual shod runners attempting the minimalist shoes with actuator lugs. Although we did not find significant differences in the impact loading, runners in minimalist shoes with lugs may experience higher vertical loading rates, with a small effect size (Cohen's d = 0.355 in VALR, Cohen's d = 0.304 in VILR), which is likely due to the increased initial vertical stiffness. These findings are in accord to previous studies which tested habitual shod runners during minimalist running (An et al., 2015; Cheung and Rainbow, 2014; Willy and Davis, 2014).

In our study, we allowed 10 minutes for adaptation and we did not provide any instruction to participants for any landing pattern modification. Another study used a 2-week transitioning program reported similar findings with ours (Willson et al., 2014). However, another study which used a 7-week protocol demonstrated a change in the landing pattern (Moore et al., 2015). Most importantly, both studies found a significant increase in VALR or VILR when running in minimalist footwear. Interestingly, previous protocols with explicit instructions have been shown to be effective in modifying landing pattern and lowering the impact loading, even the participants were running in their usual shoes (Chen et al., 2016). Considering the relationship between vertical loading rates and running-related injuries (Davis et al., 2004; Pohl et al., 2008; Worp et al., 2016; Zadpoor and Nikooyan, 2011), running in minimalist shoes with actuator lugs without any systemic training or instructions may put the runners at a higher injury risk.

Another claim of that novel shoe design is enhanced energy efficiency. However, the present study observed a higher energy loss when running in minimalist shoes with lug platform. Such increase in the energy loss may be explained by the increased initial vertical stiffness, as the hysteresis loop during the push-off phase in two shoe conditions were almost overlapping (Figure 9.2). It also indicated that the lugs did not enhance energy conversion during the push-off phase.

A higher initial vertical stiffness may be the main reason for the additional energy loss, which is also supported by a previous study (Jonathan Sinclair et al., 2016). Besides initial vertical stiffness, the energy return was not enhanced during the push-off phase. As most of the runners in this study maintained a RFS landing when running in the new shoe model, it might impede the deformation and the energy return process of the actuator lugs (Nigg and Segesser, 1992). A previous study reported an improvement in running economy in elite runners when running in a similar shoe model (Moran and Greer, 2013), which is supposed to lead to a more efficient energy exchange during running (Gruber et al., 2013; Ogueta-Alday et al., 2014). Compared to that particular study, our study showed contradictory result when analysing the energy exchange using a biomechanical approach. One possible reason may be that the participants included in the previous study were elite runners, among which non-RFS runners might take a larger proportion than recreational runners (Hasegawa et al., 2007; Larson et al., 2011). As the previous study did not report data regarding the landing pattern, such argument remains speculative.

Several limitations should be considered in light of these findings. First of all, we did not collect kinematic data of individual joints in the lower extremities. According to a post-hoc sample size estimation using the current VALR result, with type II error β= 0.632, a sample size of 51 participants would be required to confirm there are no significant difference in vertical loading rates. The present study examined the immediate effects of a novel footwear design in naive minimalist runners. Future study is warranted to investigate the running mechanics after a longer adaptation period.

9.5 Conclusion

Habitual shod runners presented a higher tendency to land with a non-RFS when they were running in minimalist shoes with lug platform than traditional running shoes. However, the vertical loading rates were similar between two footwear conditions. Although the minimalist shoes with lug platform claimed to promote energy exchange during impact, we observed a greater energy loss in this novel shoe condition, which may be attributed to the increase in the vertical body stiffness during initial contact.

9.6 Project dissemination

Journal publication

Zhang JH, McPhail AJC, An WW, Naqvi WM, Chan DLH, Au IPH, Luk ATW, Chen TLW, Cheung RTH. (2016) A new footwear technology to promote non-heelstrike landing and enhance running performance: Fact or fad? *Journal of Sports Sciences*, 35,15:1-5

Conference proceeding

Zhang JH, McPhail AJC, An WW, Naqvi QM, Chan DLH, Au IPH, Luk ATW, Chen TL, Cheung RTH (2016) Effects of a new running shoe design on the landing pattern and energy loss. The 21st Annual Congress of the European College of Sport Science, 6-9 July 2016, Vienna.

CHAPTER 10
EXPLOTRATORY STUDY INTO THE INNATE BIOMECHANICAL PARAMETERS RELATED TO RUNNING PERFORMANCE

10.1 Introduction

Distance runners from Africa, such as Kenya and Ethiopia, have dominated major marathon races for many years. Physiological advantages, such as a better running economy, have been reported to contribute to such an outstanding performance (Santos-Concejero et al., 2017). Based on previous studies, some biomechanical parameters, such as lower cadence (Tartaruga et al., 2012), longer stride (Tartaruga et al., 2012), and shorter contact time (Di Michele and Merni, 2014), could associate with a better running economy, which would contribute to a better running performance (Tartaruga et al., 2012). Additionally, elite runners are more likely to land with a midfoot (MFS) or forefoot (FFS) strike than rearfoot strike (RFS), when compared with recreational runners (Hasegawa et al., 2007). Kinetically, peak vertical ground reaction force (GRF) and peak braking force, which is thought to indicate energy loss during contact (Støren et al., 2011), may inversely correlate with running economy (Støren et al., 2011).

However, opposite findings have been reported. For example, a distinct association between gait-related parameters (e.g. stride length and cadence) and running economy was not observed in a group of elite African runners (Santos-Concejero et al., 2017). Similarly, a weak relationship has been reported between running economy and performance among elite African runners (Mooses et al., 2015). These conflicting results may be due to the homogeneity of the runner group, among which the variance of running economy was small (Santos-Concejero et al., 2017). Thus, a comparison between African runners and runners from other regions at different performance levels might bring more insights to explain the exceptional running performance in African runners. Whether these biomechanical parameters are innate attributes among African runners or developed during training remains unclear.

Hence, this case study sought to provide preliminary evidence by comparing these biomechanical parameters between elite and recreational distance runners from Africa and Asia. We hypothesized that some parameters might be associated with training, while some may be innate to African runners regardless of the performance level.

10.2 Methods

10.2.1 Participants

Four groups of runners were invited to participate in this study, including 1) Elite African runners; 2) Elite Asian runners; 3) Recreational African runners; 4) Recreational Asian runners. We defined an elite runner as who was able to finish a full marathon competition within 3:00:00. This finishing time was selected because it is a commonly used guaranteed entry limit for a few international marathon competitions, such as the Boston Marathon (“Qualify | Boston Athletic Association,” 2018). To be regarded as recreational runners, the participant should not have previous experience in marathon competition and had not been running on a regular basis in the past 12 months (Buist et al., 2010).

Twenty male runners (age = 29.7±6.0 years old, body height = 1.72±0.06 m, body weight = 61.0±10.3 kg) participated in this study. They were classified into four groups as 1) elite African runners; 2) elite Asian runners; 3) recreational African runners; 4) recreational Asian runners. Each group comprised five runners and the demographic data for each group is listed in Table 10.1. All the participants were free from any active lower limb injury upon recruitment. We obtained written consents from each participant and the experimental procedure was approved by the institutional review board of the Hong Kong Polytechnic University.

Table 10.1 Demographic data from the twenty participants

Type of the runners	Age (yo)	Height (m)	Weight (kg)
Elite African runner	34.0±7.4	1.69±0.03	54.9±2.8
Elite Asian runner	30.2±7.3	1.72±0.05	60.7±9.2
Recreational African runner	28.8±1.9	1.75±0.10	63.8±16.3
Recreational Asian runner	25.6±3.4	1.72±0.05	64.6±8.6

10.2.2 Experiment procedures

Reflective markers were firmly affixed onto specific landmarks according to a previously established model (Altman and Davis, 2012). After a 10-minute treadmill adaptation, each participant ran at 12 $km \cdot h^{-1}$ on an instrumented treadmill (AMTI, Watertown, MA, USA) for three minutes. During running, we collected the ground reaction force at 1,000 Hz and captured the marker trajectories using a motion capture system (Vicon, Oxford, UK) at 200 Hz. The data were then filtered using a fourth-order, Butterworth, low-pass filter with a cut-off frequency at 50 Hz for the GRF, and 8 Hz for the kinematics data (Altman and Davis, 2012).

Data from all the footfalls in the last minute of each running trial were analysed. Stance phase was detected using a cut-off threshold of 10 N (Zhang et al., 2016). The contact time was subtracted by calculating the time difference between foot-contact and toe-off. Cadence was defined as the total number of strides made per minute. Stride length was calculated by multiplying treadmill and the time between successive initial contacts of the same foot (Chan et al., 2018a). Footstrike angle (FSA) was calculated based on the method described in Chapter 2.3, and each FSA was classified into a rearfoot (RFS), midfoot (MFS), or forefoot (FFS) strike landing pattern based on a previous study (Altman and Davis, 2012). Body mass normalized anterior-posterior and vertical GRF were extracted and anterior-posterior GRF was subdivided into peak braking force and peak propulsion force for analyses.

10.2.3 Statistical analysis

Non-parametric data analysis was used in this study because of the small sample size. Parameters analysed in this study included stride length, cadence, contact time, peak vertical force, peak braking force, peak propulsion force, and FSA. These parameters were compared between Asian and African runners at different performance levels using Mann-Whitney-Wilcoxon tests. Effect sizes (Cohen's *d*) of region and training for each parameter were calculated. The benchmarks to define a small, medium, and large effect size were 0.3, 0.5, and 0.8 (Cohen, 1992).

10.3 Results

African runners presented lower footstrike angle than Asian runners in both performance levels (*p*s = 0.028-0.048, Cohen's *ds* = 1.30-1.70). As shown in Figure 10.1, African runners mostly landed with a MFS pattern. In contrast, Asian runners, especially Asian recreational runners, tended to land with RFS pattern.

Kinetic parameters are shown in Figure 10.2. Elite runners experienced higher vertical ground reaction force in spite of their regions (*p*s = 0.016-0.028, Cohen's *d*s = 1.09-1.55). African elite runners exerted higher peak propulsion force than African recreational runners (*p* = 0.008, Cohen's *d* = 1.94), while Asian elite runners exhibited higher braking force than the recreational runners from the same ethnicity (*p* = 0.048, Cohen's *d* = 1.51).

Among the temporal-spatial parameters (Figure 10.3), African recreational runners showed higher step rates with shorter stride length compared to recreational runners from Asia (*p* = 0.048, Cohen's *d* = 1.38), but such difference was not observed between elite runners from the two regions (*p* = 0.14, Cohen's *d* = 0.40). African elite runners presented with shorter contact time than African recreational runners (*p* = 0.016, Cohen's *d* = 1.00), while Asian runners did not present such difference (*p* = 0.42, Cohen's *d* = 0.30).

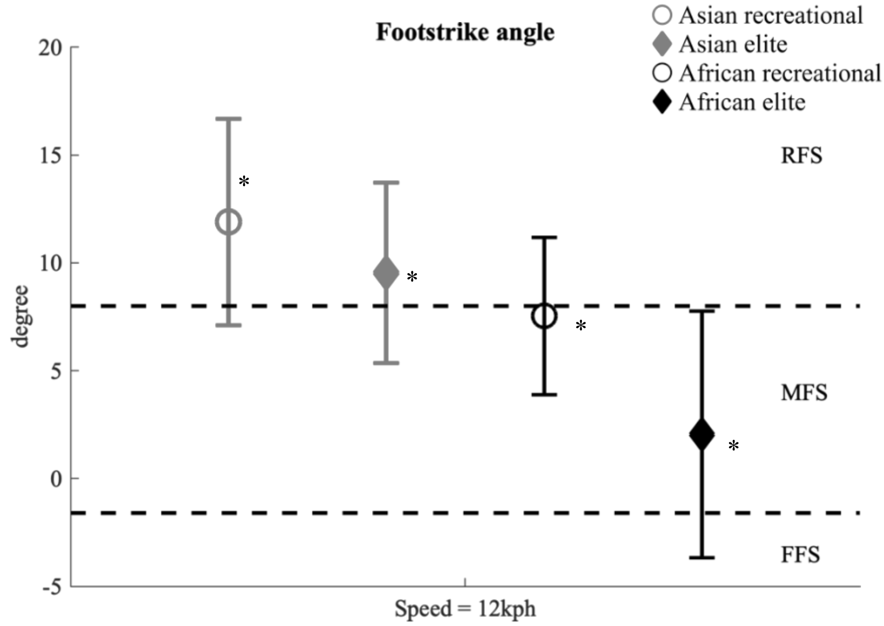

Figure 10.1 Comparison of footstrike angle among four groups of participants

* Significant difference between two regions

$ Significant difference between two performance levels

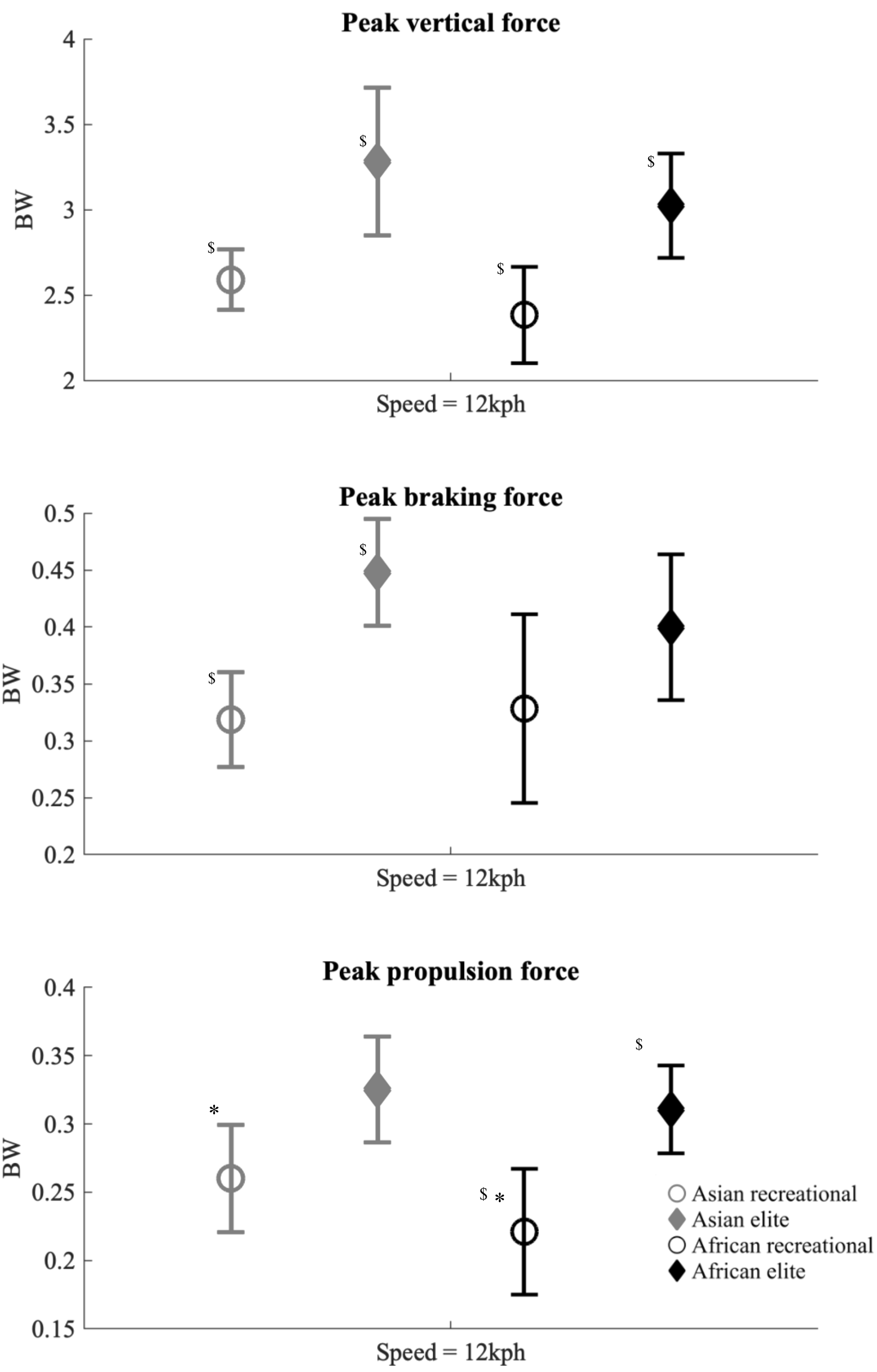

Figure 10.2 Comparison of kinetics parameters among four groups of participants

* Significant difference between two regions

$ Significant difference between two performance levels

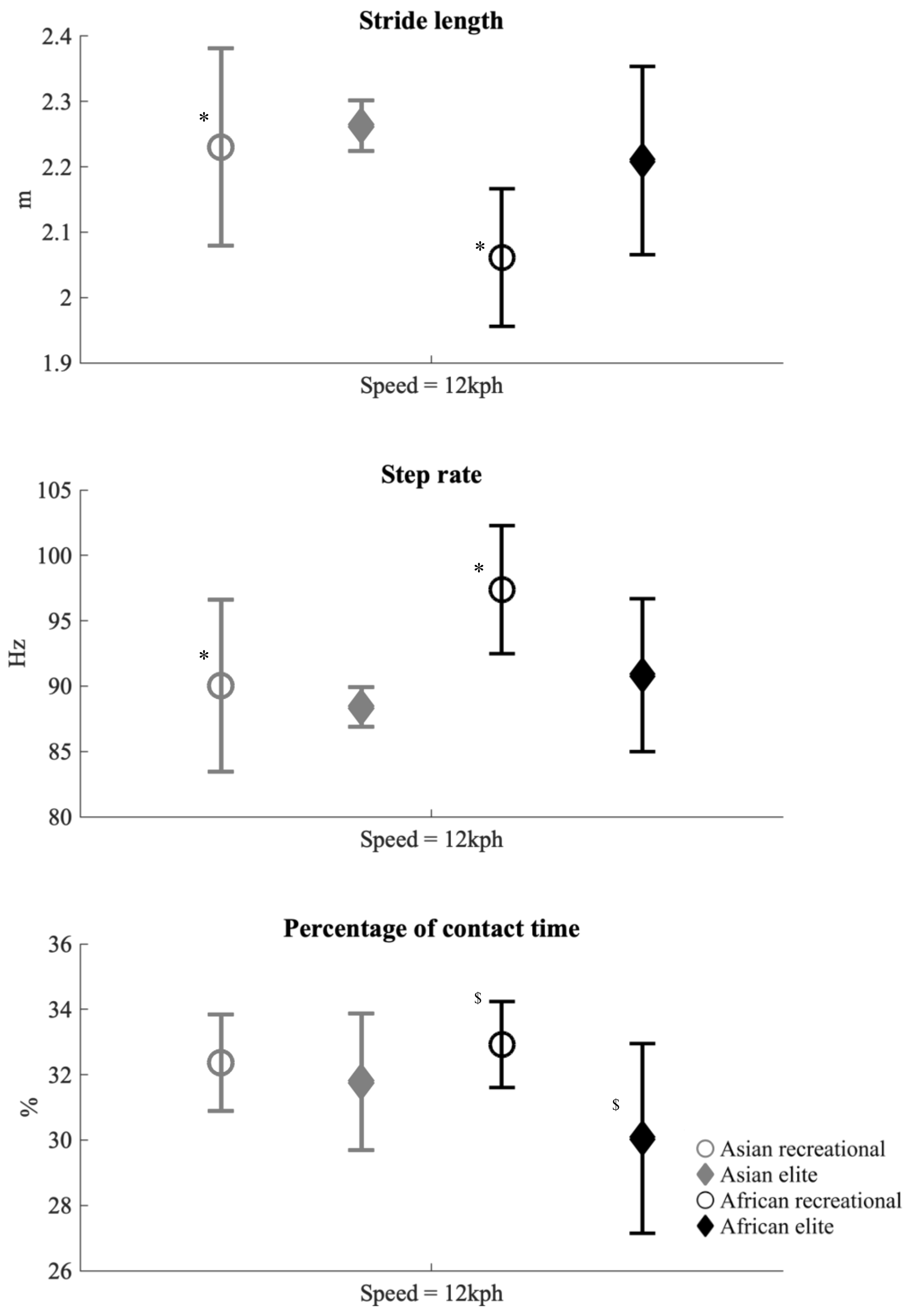

Figure 10.3 Comparison of temporal-spatial parameters, including stride length (a), step rate (b), percentage of contact time (c), among four groups of participants

* Significant difference between two regions

$ Significant difference between two performance levels

10.4 Discussion

This study explored the region- and training-specific biomechanical parameters among runners from Africa and Asia between two performance levels. Based on the findings of this study, we found that African runners tend to land using a non-RFS pattern. Meanwhile, elite runners demonstrated shorter contact time compared to recreational runners. Moreover, elite runners experienced higher vertical ground reaction force and propulsion force than recreational runners regardless of the region.

Both elite and recreational runners from Africa expressed lower FSA compared to Asian runners at the same performance level. Previous studies showed inconsistent findings regarding the region effect on FSA (Hatala et al., 2013; Hollander et al., 2018; Lieberman et al., 2010). It was suggested that African runners land with a MFS or FFS pattern because they could be more habituated to barefoot conditions in their daily activities (Lieberman et al., 2010), which is in accordance with our current findings. Moreover, FFS or MFS has been shown to associate with less oxygen consumption and better running economy (Cheung and Ngai, 2015), which could promote performance in distance running.

Our results did not suggest any region- or training-specific temporal-spatial parameter. Previous studies showed that well-trained runners presented with higher step rate (Hunter et al., 2017) and shorter contact time (Santos-Concejero et al., 2017) than recreational runners. Post-hoc power analysis indicated the power equals to 0.46, and a sample with 10 runners in each group would be required to confirm such statistical non-significance.

Kinetically, elite runners in this study experienced higher peak vertical ground reaction force than recreational runners, regardless of their ethnicity. Meanwhile, elite runners experienced higher braking/propulsion force than the recreational runners from Asia/Africa. Previously, a higher ground reaction force was considered negatively associated with running performance. However, more recent studies reported that elite runners applied higher force than recreational counterparts (Santos-Concejero et al., 2017), which is in accordance with our findings. The increased force could relate to a faster mass deceleration and acceleration during the stance phase, which could lead to a better running performance (Hunter and Smith, 2007) and running performance (Weyand et al., 2000).

The relatively small sample size limited the application of the findings of this current study. The present study did not examine individual joint kinematics, which could generate a full picture of region and training effect on distance running performance.

10.5 Conclusion

Based on the findings in this study, we suggest that footstrike angle could be an innate attribute in African runners. Meanwhile, elite runners tend to present higher peak vertical force and propulsion force within a shorter contact time during running, compared to recreational runners.

10.6 Project dissemination

Journal publication

Zhang JH, An WW, Au IPH, Chan ZYS, Lau FOY, Cheung RTH. (2019) Comparison of the biomechanical parameters between elite and recreational distance runners from Africa and Asia: a case study. *International Journal of Sports Physiology and Performance* (in preparation)

Conference proceedings

Zhang JH, Chan ZYS, Au IPH, Lau FOY, An WW, Cheung RTH. (2018) A case study to identify potential innate biomechanical parameters in African distance runners: Comparison with Asian runners at different performance levels, 11^{th} Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Poster Presentation Award)**

Zhang JH, An WW, Au IPH, Chan ZYS, Lau FOY, Cheung RTH (2016) Comparison of biomechanical parameters between elite and recreational marathon runners from Hong Kong and Africa. The 5th HKASMSS Student Conference on Sports Medicine, Rehabilitation and Exercise Science 2016, 26 November 2016, Hong Kong SAR

CHAPTER 11
APPLICATION OF AN ARTIFICIAL NEURAL NETWORK MODEL IN FOOTSTRIKE ANGLE PREDICTION

11.1 Introduction

Footstike angle (FSA) can be used to classify a runner's landing pattern, including forefoot strike (FFS), midfoot strike (MFS), and rearfoot strike (RFS) (Altman and Davis, 2012). Footstrike angle and landing pattern have been considered as important kinematics parameters since their potential relationship with running economy (Cheung et al., 2016; Hasegawa et al., 2007; Kasmer et al., 2013) and running injury risk (Cheung and Davis, 2011). However, the measurement of FSA requires a motion capture system, which limits its application in the outdoor environment.

Previous studies proposed different surrogate methods to predict FSA in an outdoor setting (Eskofier et al., 2013; Giandolini et al., 2014). One commonly used method was to measure the time between the peak vertical acceleration at the heel and the fifth metatarsal head (THM) (Giandolini et al., 2014). However, this THM method showed inconsistent prediction accuracy, varying from 80% accuracy to below 10% (Gaudel et al., 2015; Giandolini et al., 2014). Moreover, the THM model has only been tested during running on level surface, with its performance during uphill or downhill running conditions remains unknown.

Artificial neural network (ANN) has been proposed to be a powerful tool in biomechanical studies (Aminian et al., 1995; Favre et al., 2012). It could be used to predict biomechanical parameters, especially when no explicit relationship was known between measurements and the data of interest. The ANN model used in previous biomechanical studies was usually a multi-layer feedforward perceptron model with back propagation (Favre et al., 2012). Such method was considered time-consuming due to the weight (ω) tuning process. Recently, a model using decorrelated neural network ensembles (DNNE) with random weights demonstrated high efficiency and effectiveness in the construction of a neural network (Alhamdoosh and Wang, 2014).

Thus, this study sought to employ the DNNE method to predict FSA based on the acceleration data measured at the heel and fifth metatarsal in a group of runners with varied landing patterns and running surface inclinations. We also compared the accuracy of the DNNE model with the previous THM method. It was hypothesized that the DNNE model would show higher accuracy in FSA prediction when running on different surface inclinations with all three landing patterns than the THM method.

11.2 Methods

11.2.1 Experiment procedures

Five healthy participants were included in this study (4 females, age = 25 ± 6 years, height = 1.63 ± 7.83 m, body mass = 54.6 ± 7.3 kg). Written consents were obtained prior to participation.

All the participants were asked to run on an instrumented treadmill (AMTI, Watertown, US) at a self-selected running speed on three running surface inclinations (level, 10% uphill and 10% downhill). During each running condition, they were instructed to run at a natural landing pattern and then were instructed to land with RFS, MFS, and FFS pattern in a randomized order. Each running trial lasted for three minutes. To provide real-time feedback of the runner's landing pattern, two reflective markers were attached onto the right foot based on the method described in Chapter 2.3. Meanwhile, two tri-axial accelerometers (±24 g, Noraxon, Arizona, US) were attached to the heel and at the fifth metatarsal head above the midsole on the external surface (Figure 11.1).

The marker trajectories were collected at 200 Hz using a Vicon eight-camera motion capture system (Vicon, Cambridge, UK), and filtered at 8 Hz using a fourth order Butterworth lowpass filter. The acceleration and the ground reaction force data were collected at 1,000 Hz, and filtered with a cut-off frequency of 50 Hz using a fourth order Butterworth lowpass filter.

11.2.2 Data analysis

Vertical ground reaction force was used to determine footstrike and toe-off during running. Footstrike angles (FSA) were calculated based on the method described in Chapter 2.3. In total, seven variables extracted from the acceleration data were used to construct the FSA prediction model using the DNNE method (Table 11.1). Peak accelerations in vertical and anterior-posterior directions were detected as a prominent spike (Eskofier et al., 2013). The time interval between peak vertical acceleration measured at heel and metatarsal was denoted as THM. Running surface inclinations were marked, using -1 for downhill running, 1 for uphill running, and 0 for level running. The constructed model was validated using a cross-validation method. Data collected from four participants were used to construct the prediction model data from the last one participant was used for validation. Based on the predicted FSA, the landing pattern can be classified into three types (RFS, MFS, and FFS) according to a previous study (Altman and Davis, 2012).

Besides, we constructed a linear regression model between THM and FSA based on the method described in a previous study (Giandolini et al., 2014). The same cross-validation method was used to validate this regression model, and the accuracy rate was compared with the prediction model constructed using the DNNE method.

11.2.3 Statistical analysis

Pearson's correlation was conducted to assess the association between the measured FSA and the FSA predicted through THM method and the DNNE model. Bland and Altman's plot was used to assess the agreement between the predicted FSA and the measured FSA. Pearson's R, mean absolute difference (MAD), root mean square error (RMSE) of the measured FSA and predicted FSA were calculated and the results from the two models were compared. The statistical package, SPSS for Windows, version 18, (SPSS software, Chicago, IL, USA). Global α level was set at 0.05.

Heel accelerometer Metatarsal accelerometer

Figure 11.1 Position of the accelerometers and the reflective markers

Table 11.1 Description of the inputs for the neural network

Variables	Unit	Description
THM	s	Time between heel and metatarsal peak vertical acceleration
VP_h	g/kg	Peak heel vertical acceleration, normalized by body mass
AP_h	g/kg	Peak heel anterior-posterior acceleration at t_0, normalized by body mass
VP_{fm}	g/kg	Peak metatarsal vertical acceleration, normalized by body mass
AP_{fm}	g/kg	Peak metatarsal anterior-posterior acceleration at t_0 + THM, normalized by body mass
Body mass	kg	--
Running inclination	0/±1	0: Level running; ±1: ±10% surface inclination

11.3 Preliminary results

A DNNE model with 12 hidden neurons and 7 random vector functional links were determined based on the pilot data. A regression model based on the THM method was calculated and shown as:

$$FSA(^{0}) = THM(s) \times 236.97 + 4.14$$

11.3.1 Foostrike angle estimation

The Pearson's R, mean absolute difference (MAD) and root mean square error (RMSE) between the estimated FSA and measured FSA were calculated, and the results are shown in Table 11.2. The FSA predicted through the ANN model showed lower MAD as well as a lower RMSE than the THM method. Bland and Altman's plot (Figure 11.2) showed agreement between the measured FSA and the FSA predicted in the DNNE model.

11.3.2 Landing pattern classification

The ANN model generated from the training sample identified 98.57% of RFS, 95.04% of MFS, and 66.90% of FFS, with a total accuracy of 95.6%. The THM model recognized 89.71% of RFS, 74.93% of MFS and 46.26% of FFS, with an overall accuracy of 76.21%. Both the ANN model and the THM model showed relatively good performance in classifying the RFS and FFS in the validation sample, with an accuracy rate at 100% in RFS, 92.5 – 100% in FFS, while the DNNE model showed higher accuracy (57.9%) over THM regression model (42.1%) in MFS prediction.

Table 11.2 Comparison of Pearson's R, MAD and RMSE of footstrike angle calculated using DNNE method and toe-heel method (THM)

	Training		Validation	
	DNNE[1]	THM[2]	DNNE	THM
Pearson's R	0.946	0.829	0.952	0.900
MAD (°)	1.650	3.314	3.665	3.714
RSME (°)	2.281	3.931	4.196	4.394

1. Estimated FSA using DNNE model

2. Estimated FSA using THM model

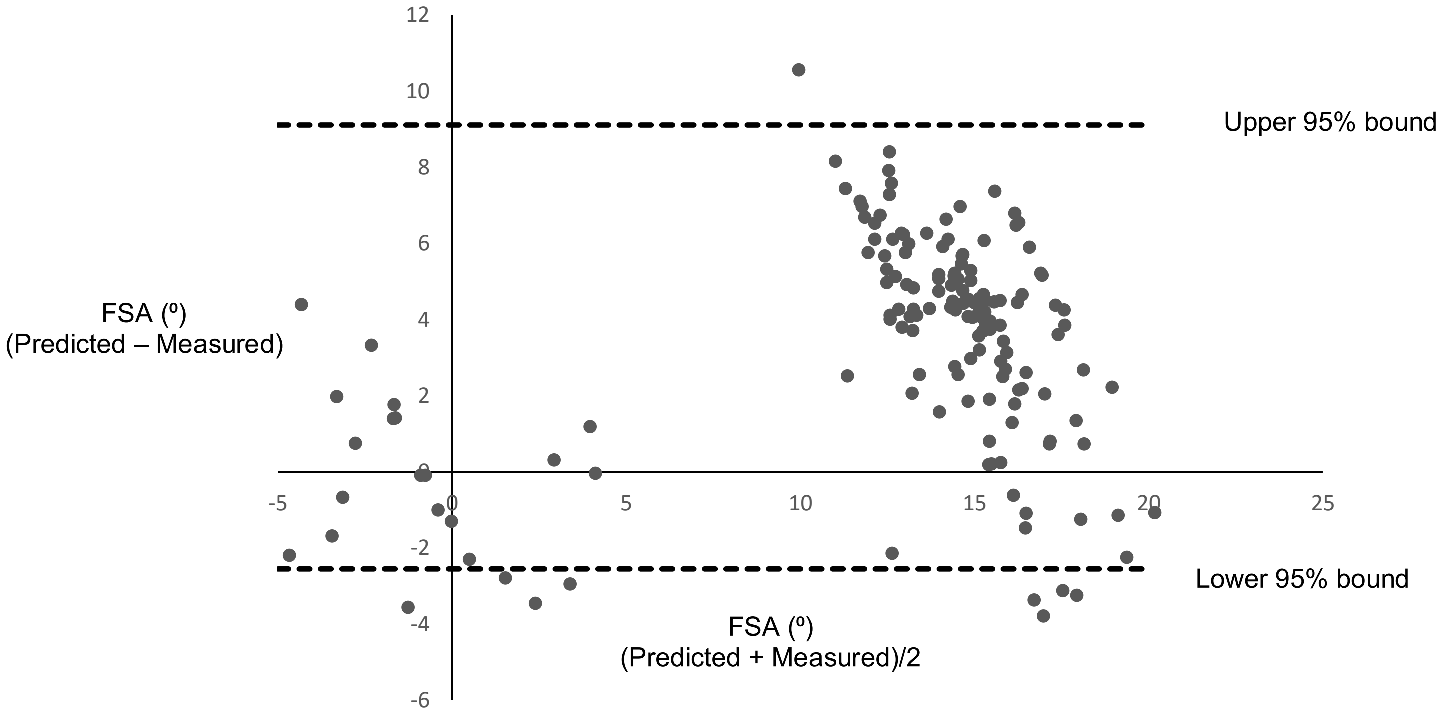

Figure 11.2 Bland and Altman in the validation sample

11.4 Discussion

This study demonstrated that the DNNE method could be used to construct an artificial neural network model to predict FSA. Compared with the previous regression model using time between heel and metatarsal peak acceleration, Our results showed higher accuracy rate in FSA prediction. This model can also be adopted in FSA prediction among varied running slopes and running speeds.

Based on our data, the DNNE model showed a higher accuracy rate, lower MAD and RMSE, when compared with THM method. Moreover, the DNNE model also outperformed in differentiating between MFS and FFS. The higher accuracy of the DNNE model could be due to the inclusion of the peak acceleration data in the model construction, which was shown associated with the footstrike pattern (Gottschall and Kram, 2005; Zhang et al., 2016). In both the training sample and the validation sample, the included strides covered running on three surface inclinations (level running, 10% of uphill and 10% downhill running). The result in the validation sample demonstrated that the FSA predicted through the DNNE model can be maintained across different running slopes.

Compared to the traditional feedforward multi-layer perceptron method to construct an artificial neural network model, the DNNE model reduced training time and demonstrated a better prediction. As the dataset for the current model construction only included four runners, among which female runners took a larger proportion, it may limit the application of this model. Moreover, the running speed used in this study only covered a limited range. We therefore proposed a future study with larger sample size and more balanced gender proportion.

11.5 Conclusion

This study aimed to introduce a novel artificial neural network method into the prediction of a biomechanical parameter, footstrike angle. The result of this study showed promising result and could be used as a surrogate measurement of footstrike angle in outdoor running experiments. Moreover, it may be applied to the production of wearable sensors for runners to record their landing pattern during daily running exercise.

CHAPTER 12
A WEARABLE EXOSUIT TO CORRECT STROKE SURVIVIORS' GAIT

This chapter introduced a side-project being done during a lab attachment in the Harvard Biodesign Lab, in School of Engineering and Applied Science in Harvard University. This project aims to develop a knee exosuit targeting on stroke rehabilitation. The device described in this chapter is the first version of this knee exosuit. Preliminary data from two patients were shown and discussed here.

12.1 Introduction

Knee hyperextension is a common pathological gait in stroke victims caused by impaired control of the quadriceps (Perry et al., 1992). Knee hyperextension is described as an excessive knee extension (> 5°) during stance phase (Loudon et al., 1998), resulting in an increased knee flexor moment and a reduced or absent knee extensor moment (Neckel et al., 2008). Knee hyperextension is not only affecting the joint alignment, but it can cause pain and increase the risk of degenerative joint disease (Perry et al., 1992).

Actuated wearable exosuit has provided a method to enhance and optimize walking gait for stroke survivors. Previous actuated ankle-foot-orthosis exosuit device has demonstrated an advantage in providing torque required in human gait (Grimmer et al., 2019), avoiding faulty walking biomechanics (Awad et al., 2017), and controlling metabolic cost (Bae et al., 2018). However, yet there are limited studies targeting correction of knee hyperextension and increase the stability of the knee during walking in this patient cohort.

This study introduced a prototype of an actuated knee exosuit aiming to provide additional torque to extend the knee during stance while restricting hyperextension of the knee joint (i.e., maximum knee extension at 0°). We hypothesized that this exosuit could reduce the muscle activation of knee flexors while maintaining the activation level of knee extensors. We also expected that stroke survivors would apply a higher amount of ground reaction force on their paretic side with the exosuit.

12.2 Methods

12.2.1 Soft exosuit & Offboard actuator

The structure of the knee exosuit is shown in Figure 12.1 (a). One motor driven offboard actuator was used to generate assistive force based on the gait cycle information (Figure 12.1 b). Gait cycle information, such as foot-contact and toe-off, was provided by two gyroscopes attached on the lateral side of ankles (Figure 12.1 a). The algorithm to detect gait cycle information was described in a previous study (Bae et al., 2015).

One Bowden cable was used to transmit the force from the offboard actuator to the soft exosuit attached to the knee. A load cell was connected to the Bowden cable to measure the force being transmitted. The sheath of Bowden cable was mounted on a 0.15-m moment arm hinge, and the inner cable was connected to the lower part of a shank wrap. When assistive force was generated, the shortened inner cable would generate a rotational torque which straightened the knee hinge (Figure 12.1 a). Since both ends of the hinge were inserted to the thigh and shank, the hinge motion would extend the knee joint. There was a hard stop embedded in the hinge which limited the knee extension angle at 0°.

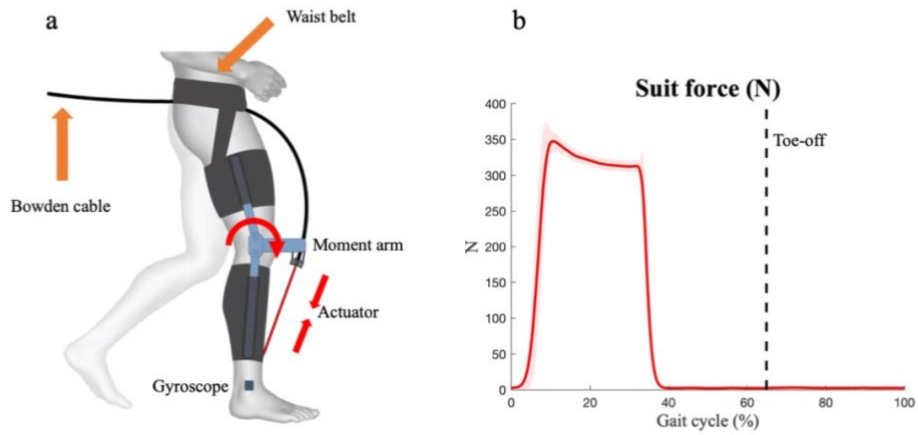

Figure 12.1 The prototype of the soft exosuit (a) and force delivered by the actuator in a gait cycle (b)

12.2.2 Data collection

Stroke survivors who had a cerebrovascular accident for more than six months were invited to join this study. The inclusion criteria included being between the ages of 25 and 75 years old, able to walk unaided on a treadmill without stopping for at least 3 minutes, and with maximum knee extension angle higher than 5 degrees during stance phase. Participants exclusion criteria included serious co-morbidities, an inability to communicate or be understood, and experiencing two falls in the past month. Medical clearance and signed consent forms approved by the Harvard University Human Subject Review Board were obtained for all participants before data collection.

To identify the maximum knee extension angle during stance phase, a screening test was conducted before participation. Forty reflective markers were attached to the lower limb of each participant according to a previous model (Awad et al., 2017). The participants were asked to walk on a 10-meter track at their self-selected walking speed, and the marker trajectories were captured at 100 Hz using a 14-camera motion capture system (Qualisys, USA). The marker trajectories were then filtered with a 10 Hz Butterworth lowpass filter (MATLAB, USA). Joint angles were calculated using filtered marker trajectories through an inverse kinematics approach (Visual 3D, C-Motion, MD, USA). In the end, two stroke survivors were recruited for the treadmill test in this study. The demographic data of the two participants is shown in Table 12.1.

During the treadmill test, the participants were asked to walk on an instrumented split-belt treadmill (Bertec, Columbus, OH, USA) at a self-selected walking speed for two trials. The first walking trial involved a walking test with the knee exosuit unpowered (SLACK), and the second walking trial with the exosuit providing active assistance (ACT). During the ACT condition, the exosuit delivered knee extension torque, which was calculated by multiplying the force recorded by the load cell and the moment arm length (0.15 m). The maximum assistive force level was set at 350 N. Each walking trial lasted for 3 minutes, and the ground reaction force data during walking were collected at 1,000 Hz. Synchronized muscle activity data were collected from the rectus femoris and bicep femoris long head using wired EMG system recording at 2,000 Hz (Delsys, Boston, MA, USA).

Table 12.1 Demographic data of the two stroke survivors

	Subject #1	Subject #2
Gender	F	M
Age (years old)	56	59
Body height (m)	1.65	1.78
Body weight (kg)	59.9	74
Paretic side	Right	Left
Treadmill walking speed (m/s)	0.90	0.78

12.2.3 Data analysis & Statistical analysis

The ground reaction force data in the vertical and anterior-posterior directions were filtered using a Butterworth lowpass filter with a cutoff frequency set at 8 Hz (Yandell et al., 2017). The EMG data were filtered using a 20-450 Hz band-pass filter, full-wave rectified, and low-pass filtered at 4 Hz to create a linear envelope (Shao et al., 2009). EMG signals for each muscle were normalized to the peak value of the baseline condition (Lerner et al., 2017). The data collected during the walking trials were normalized to each gait cycle and averaged across gait cycles for each trial.

Numerical integration was conducted for the EMG signal across each gait cycle. Peak vertical ground reaction force and peak propulsion force in each gait cycle were calculated. Descriptive analysis was conducted with means and standard deviations (SDs) from the paretic limb compared between SLACK and ACT conditions.

12.3 Results & Discussion

Both participants showed a reduced muscle activation in the long head of bicep femoris (Figure 12.2, Sub #1 reduced by 9.04% and Sub #2 by 16.60%). Sub #1 also reduced muscle activation in the rectus femoris by 23.97% when the suit was activated. On the other hand, Sub #2 increased the rectus femoris activation by 3.43%. Kinetically, both participants applied higher force onto the ground. Sub #1 experienced 9.6% higher peak vertical ground reaction force when the suit was activated. The peak vertical force during the ACT condition remained similar with the SLACK condition for Sub #2, but the peak propulsion force increased by 35.29% in the ACT condition compared to the SLACK condition (Figure 12.2).

The exosuit proposed in this study was designed to provide additional torque to extend the knee during walking. As expected, we observed a reduced muscle activation in the long head of bicep femoris. This proposed exosuit is so far the first version to generate extra knee extension torque and enhance walking performance for stroke survivors. This version of knee extension exosuit revealed similar effect in reducing muscle activation demand when compared to a previous knee exosuit which aimed to facilitate knee flexion (Sridar and Polygerinos, 2017). Meanwhile, the two participants experienced a higher amount of ground reaction force on their paretic limb during walking when the suit was activated, which could potentially relate to a reduced metabolic cost as observed in a previous study (Awad et al., 2017).

The participants were expected to maintain a similar muscle activation level in knee extensors with the use of the exosuit. While we observed a slight change in rectus femoris activation in one participant (Sub #2), the other participant showed more than 20% reduction in rectus femoris when the suit was activated. Such variance could be due to the heterogeneity of post-stroke motor impairment, which could lead to variance in individual responsiveness to the actuated exosuit (Awad et al., 2017; Lerner et al., 2017). With the amount of total knee extensor moment unknown, the current investigation could not assess the performance of the exosuit in increasing extensor torque during walking. A further study with inverse kinetics analysis would provide us more detailed information about the total amount of knee extensor torque experience by the participants.

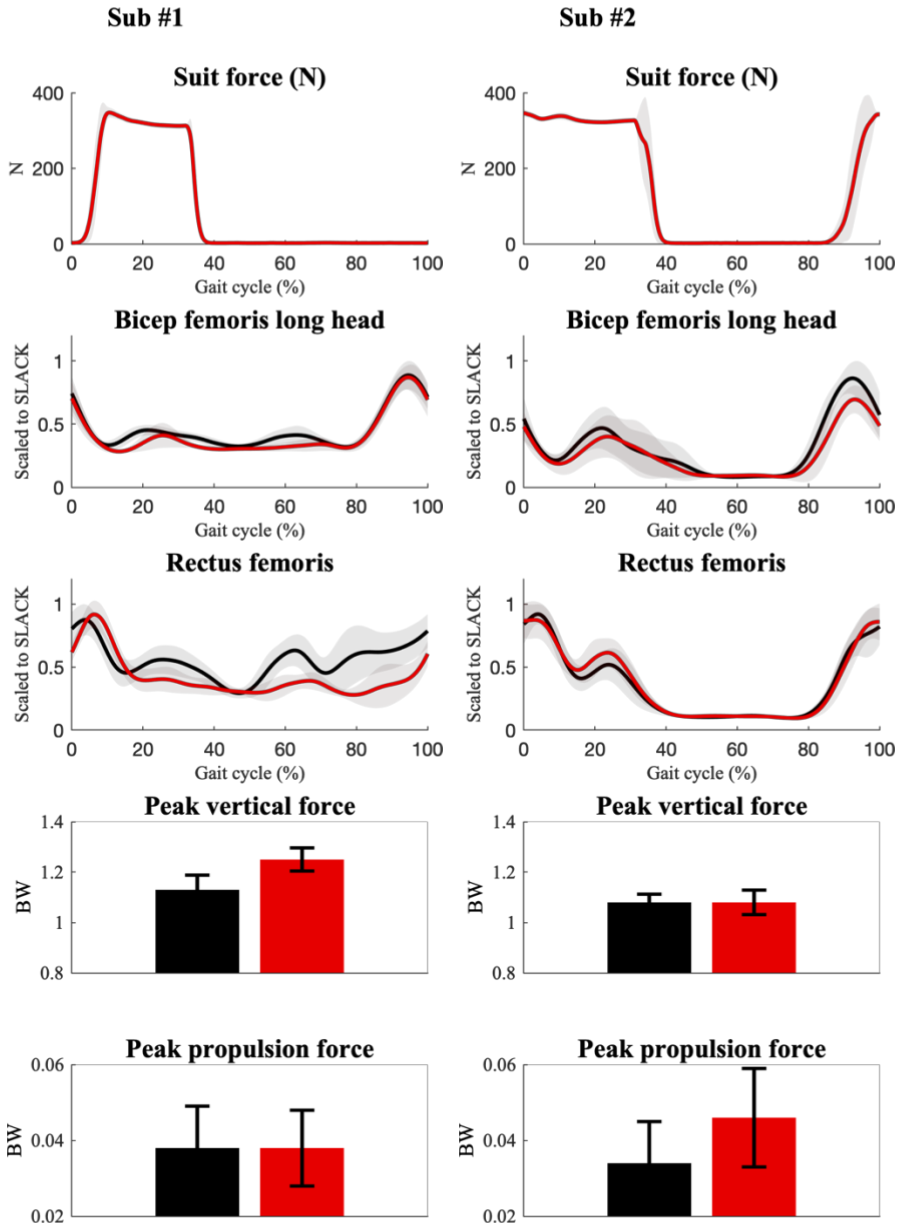

Figure 12.2 Comparison of muscle activation, peak vertical ground reaction force, and peak propulsion force during SLACK (black) and ACT (red) conditions

12.4 Conclusion

A preliminary results indicate a reduction in knee flexor muscle by the proposed knee exosuit. Further study evaluating the lower limb walking biomechanics would be needed to understand the human-robot interface of this version of knee exosuit.

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APPENDIX I

Copyright of three publications used in this thesis

1. Journal paper used in Chapter 4

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Title: Comparison of the correlations between impact loading rates and peak accelerations measured at two different body sites: Intra- and inter-subject analysis

Author: Janet H. Zhang, Winko W. An, Ivan P.H. Au, Tony L. Chen, Roy T.H. Cheung

Publication: Gait & Posture

Publisher: Elsevier

Date: May 2016

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2. Journal paper used in Chapter 9

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Routledge Taylor & Francis Group

Title: A new footwear technology to promote non-heelstrike landing and enhance running performance: Fact or fad?

Author: Janet H. Zhang, , Aislinn J. C. McPhail, et al

Publication: Journal of Sports Sciences

Publisher: Taylor & Francis

Date: Aug 3, 2017

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3. Journal paper used in Chapter 6

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Title: Can runners maintain a newly learned gait pattern outside a laboratory environment following gait retraining?

Author: Janet H. Zhang,Zoe Y.S. Chan,Ivan P.H. Au,Winko W. An,Roy T.H. Cheung

Publication: Gait & Posture

Publisher: Elsevier

Date: March 2019

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APPENDIX II

Publications arising from the thesis

Articles published in peer-reviewed journals

5. **Zhang JH**, Chan ZYS, Au IPH, An WW, Shull PB, Cheung RTH. (2019) Transfer learning effects of biofeedback running retraining in untrained conditions. *Medicine & Science in Sports & Exercise*, DOI:10.1249/MSS.0000000000002007
6. **Zhang JH**, Chan ZYS, Au IPH, An WW, Cheung RTH. (2019) Can runners maintain the newly learned gait pattern outside laboratory environment following gait retraining? *Gait & Posture*, 69: 8-11
7. **Zhang JH**, McPhail AJC, An WW, Naqvi WM, Chan DLH, Au IPH, Luk ATW, Chen TLW, Cheung RTH. (2016) A new footwear technology to promote non-heelstrike landing and enhance running performance: Fact or fad? *Journal of Sports Sciences*, 35,15:1-5
8. **Zhang JH**, An WW, Au IPH, Chen TL, Cheung RTH. (2016) 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

Articles in preparation

4. **Zhang JH**, Chan ZYS, Cheung RTH (2019) African runners at two performance levels presented higher vertical stiffness and lower footstrike angle. *Scientific Reports*
5. **Zhang JH**, Chan ZYS, Cheung RTH. (2019) Kinetic and kinematic analysis of the learning effect of a laboratory-based gait retraining in untrained running conditions. *Journal of Science and Medicine in Sport*

6. **Zhang JH**, Jia YW, Chan ZYS, An WW, Au IPH, Xu Z, Cheung RTH (2019) An artificial neural network model to predict footstrike angle during varied runnings slopes. *PlosOne*

Conference proceedings:

12. **Zhang JH**, Kowk GHJ, Koh HY, Chan ZYS, Kwan KYH, Yip J, Cheung RTH. (2019) Gait differences between patients with adult degenerative scoliosis and healthy counterparts, The 10th Annual Meeting of Japanese Orthopaedic Society of Knee, Arthroscopy and Sports Medicine, 13-15 June, Sapporo, Japan
13. **Zhang JH**, Chan ZYS, Cheung RTH. (2019) Motor strategies and learning effect translation in an established running retraining program, XXVII Congress of the International Society of Biomechanics, 31 Jul – 4 Aug, Calgary, Canada **(Winner of Congress Travel Grant)**
14. **Zhang JH**, Chan ZYS, Au IPH, An WW, Cheung RTH. (2018) Transfer of the learning effect in outdoor conditions with varied surface inclinations upon completion of an indoor gait retraining program, 11^{th} Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Oral Presentation Award)**
15. **Zhang JH**, Chan ZYS, Au IPH, Lau FOY, An WW, Cheung RTH. (2018) A case study to identify potential innate biomechanical parameters in African distance runners: Comparison with Asian runners at different performance levels, 11^{th} Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Poster Presentation Award)**
16. **Zhang JH**, Kowk G, Koh HY, Chan ZYS, Kwan K, Yip J, Cheung RTH. (2018) Gait differences between patients with adult degenerative scoliosis and health controls, 11^{th} Pan-Pacific Conference on Rehabilitation, 17-18 Nov, Hong Kong SAR **(Winner of the Best Poster Presentation Award)**

17. **Zhang JH**, Zoe Y.S. Chan, Ivan P.H. Au, Winko W. An, Roy T.H. Cheung. (2018) Can the Newly Learnt Gait Pattern after Running Retraining be Translated to Untrained Conditions? : 1547 Board# 8 May 31, 2018, American Colleague of Sports Medicine (ACSM) Annual Meeting
18. **Zhang JH**, Ho KY, Li KK, Li KM, Mark YP, Wu HM, Sin ELL, Chan ZYS, Au IPH, An WW, Cheung RTH (2017) A highly feasible exercise program to promote executive functions in young adults. International Symposium on Physical Activity & Fitness of the Young Generation in Asia-Pacific 2017, 20 May 2017, Hong Kong SAR **(The 3rd place for the Best Poster Award)**
19. **Zhang JH**, An WW, Au IPH, Chan ZYS, Cheung RTH (2016) Kinetics control in runners at different running speeds and slopes after completion of a gait retraining program. The 5th HKASMSS Student Conference on Sports Medicine, Rehabilitation and Exercise Science 2016, 26 November 2016, Hong Kong SAR
20. **Zhang JH**, An WW, Au IPH, Chan ZYS, Lau FOY, Cheung RTH (2016) Comparison of biomechanical parameters between elite and recreational marathon runners from Hong Kong and Africa. The 5th HKASMSS Student Conference on Sports Medicine, Rehabilitation and Exercise Science 2016, 26 November 2016, Hong Kong SAR
21. **Zhang JH**, McPhail AJC, An WW, Naqvi QM, Chan DLH, Au IPH, Luk ATW, Chen TL, Cheung RTH (2016) Effects of a new running shoe design on the landing pattern and energy loss. The 21st Annual Congress of the European College of Sport Science, 6-9 July 2016, Vienna.
22. **Zhang JH**, An WW, Au IPH, Cheung RTH. (2015) Intra- and inter-subject analysis of the correlations between impact laoding rates and peak positive acceleration measured at different body sites during running.

Hong Kong Physiotherapy Association Conference. Oct 3-4, Hong Kong SAR

APPENDIX III

Other research output/deliverable during the PhD study

Grant

Development of Wearable Sensors to Measure Knee Joint Loading in Patients with Knee Osteoarthritis (ITS/143/17, Innovation and Technology Fund)

Patent

A mobile Joint Loading Tracker System for Early Screening and Progression Monitoring of Patients with Knee Osteoarthritis

APPENDIX IV

Other publications during the PhD study

1. An WW, Ting KH, Au IPH, **Zhang JH**, Chan ZYS, Davis IS, So WKY, Chan RHM, Cheung RTH. (2019) Neurophysiological correlates of gait retraining with real-time visual and auditory feedback. *IEEE Transaction on Neural Systems and Rehabilitation Engineering*. DOI: 10.1109/TNSRE.2019.2914187
2. Chan ZYS, Au IPH, Lau FOY, Ching ECW, **Zhang JH**, Cheung RTH. Does maximalist footwear lower impact loading during level ground and downhill running? *European Journal of Sport Science* (2018), DOI: 10.1080/17461391.2018.1472298
3. Cheung RTH, Au IPH, An WW, **Zhang JHW**, Chan ZYS, Ho KKW, Deluzio KJ, Rainbow MJ. (2018) Immediate and short-term effects of gait retraining on the knee joint moments and symptoms in patients with early knee osteoarthritis: a randomized controlled trial. *Osteoarthritis & Cartilage*, DOI: 10.1016/j.joca.2018.07.011
4. Ching ECK, An WW, Au IPH, **Zhang JH**, Chan ZYS, Shum GLK, Cheung RTH. (2018) Impact loading during distracted running before and after auditory gait retraining. *International Journal of Sports Medicine*, DOI: 10.1055/a-0667-9875
5. Mak DNT, Au IPH, Chan M, Chan ZYS, An WW, **Zhang JH**, Draper D, Cheung RTH. Placebo effect of facilitatory Kinesio tape on muscle activity and muscle strength. *Physiotherapy Theory & Practice,* (2018), DOI: 10.1080/09593985.2018.1441936
6. Law MHC, Choi EMF, Law SHY, Chan SSC, Wong SMS, Ching ECK, Chan ZYS, **Zhang JH**, Lam GWK, Lau FOY, Cheung RTH. Effects of

footwear midsole thickness on running biomechanics. *Journal of Sports Science* (2018), DOI: 10.1080/02640414.2018.1538066

7. Mangubat AMS, **Zhang JH**, Chan ZYS, MacPhail AJC, Au IPH, Cheung RTH. Biomechanical outcomes due to impact loading in runners while looking sideways. *Journal of Applied Biomechanics* (2017), DOI: 10.1123/jab.2017-0381
8. Chan ZYS, **Zhang JH**, Au IPH, An WW, Shum GLK, Ng GYF, Cheung RTH. (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*, DOI: 10.1177/0363546517736277
9. Au IPH, Lau FOY, An WW, **Zhang JH**, Chen TLW, Cheung RTH. (2017) Immediate and short-term biomechanical adaptation of habitual barefoot runners who start shod running. *Journal of Sports Sciences* (2017), DOI: 10.1080/02640414.2017.1313997
10. Cheung RTH, An WW, Au IPH, **Zhang JH**, Chan ZYS, Man AH, Lau FOY, Lam MKY, Lau KK, Leung CY, Tsang NW, Sze LKY, Lam GWK. (2017) Measurement agreement between a newly developed sensing insole and traditional laboratory-based method for footstrike pattern detection in runners. *PloS one*, DOI: 10.1371/journal.pone.0175724
11. Cheung RTH, An WW, Au IPH, **Zhang JH**, Chan ZYS, MacPhail AJ. (2017), Control of impact loading during distracted running before and after gait retraining in runners. *Journal of Sports Science*, DOI: 10.1080/02640414.2017.1398886
12. Fong ICD, Li WSC, Tai WKJ, Tsang TWR., **Zhang JH**, Chen TLW, H. Baur, P. Eichelberger, Cheung RTH, Effect of foot progression angle adjustment on the knee adduction moment and knee contact force in

runners with and without knee osteoarthritis. *Gait & Posture* (2017), DOI: 10.1016/j.gaitpost.2017.12.029

13. Cheung RTH, Lau FOY, Ching E, Chan ZYS, **Zhang JH**, Au IPH. (2017) Maximalist Shoes Do Not Reduce Impact Loading During Level And Downhill Running, *Medicine & Science in Sports & Exercise*, DOI: 10.1249/01.mss.0000517189.76377.fe
14. MacPhail AJ, Au IPH, Chan M, Mak DNT, An WW, Chan ZYS, **Zhang JH**, Draper D, Cheung RTH. (2017) The effect of inhibitory Kinesio tape on measured and perceived maximal grip strength. *Journal of Bodywork and Movement Therapies* (2017), DOI: 10.1016/j.jbmt.2017.10.011
15. Chen TLW, An WW, Chan ZYS, Au IPH, **Zhang JH**, Cheung RTH. (2016) Immediate effects of modified landing pattern on a probabilistic tibial stress fracture model in runners. *Clinical Biomechanics*, DOI: 10.1016/j.clinbiomech.2016.02.013

APPENDIX V

Demographic data of participants

Table V.I Demographic data of participants recruited in Chapter 4

Sub NO	Gender	Age (yo)	Body weight (kg)	Body height (m)
401	M	21	1.67	55
402	M	21	1.73	56.3
403	M	21	1.85	78
404	M	28	1.78	64.2
405	M	23	1.78	64.2
406	M	25	1.68	66.5
407	M	20	1.88	96.2
408	F	24	1.65	53.5
409	M	21	1.68	62
410	F	32	1.64	65.5

Table V.II Demographic data of participants recruited in Chapter 5

Sub ID	Gender	Age (yo)	Body weight (kg)	Body height (m)	Running experience (years)	Weekly distance (km)
501	F	38	65.5	1.60	5	20
502	M	48	53.2	1.62	10	30
503	F	38	45.6	1.55	3	30
504	M	44	67.8	1.68	4.5	30
505	M	44	59.0	1.72	10	30
506	F	41	51.9	1.65	5	100
507	M	39	67.6	1.65	3	25
508	M	43	73.9	1.76	2	20
509	M	47	58.1	1.65	10	20
510	M	46	67.4	1.70	15	20
511	M	50	60.2	1.67	5	40
512	M	28	58.3	1.66	3	14
513	M	28	64	1.69	14	15

Table V.III Demographic data of participants recruited in Chapter 6

Sub NO	Gender	Age (yo)	Body weight (kg)	Body height (m)	Running experience (years)	Weekly distance (km)
601	M	19	60.9	1.68	2	40
602	M	33	57.4	1.78	5.5	35
603	F	42	45.4	1.54	4.5	30
604	M	43	64.6	1.78	12	110
605	M	49	68.4	1.69	13	75
606	F	38	65.5	1.59	5	20
607	M	48	53.2	1.62	10	30
608	F	38	45.6	1.55	3	30
609	M	44	67.8	1.68	4	35
610	M	44	59.0	1.75	10	30
611	F	41	51.9	1.65	5	100
612	M	39	67.6	1.65	3	25
613	M	43	73.9	1.76	2	20
614	M	37	58.1	1.65	10	20
615	M	46	67.4	1.70	15	20

Table V.IV Demographic data of participants recruited in Chapter 7

Sub NO	Gender	Age (yo)	Body weight (kg)	Body height (m)	Running experience (years)	Weekly distance (km)
701	M	43	68.4	1.78	2	200
702	M	22	72.1	1.78	3	10
703	M	28	58.3	1.66	3	14
704	M	28	64	1.68	14	15
705	M	41	72.4	1.81	14	20

Table V.V Demographic data of participants recruited in Chapter 9

Sub NO	Gender	Age (yo)	Body weight (kg)	Body height (m)
901	M	20	72.3	1.84
902	M	19	66.0	1.80
903	M	21	69.2	1.77
904	M	18	57.2	1.72
905	F	20	60.9	1.66
906	M	30	87.3	1.75
907	M	30	62.8	1.71
908	F	23	49.5	1.58
909	M	27	79.5	1.75
910	M	22	57.8	1.83
911	F	20	65.5	1.66
912	M	18	65.5	1.78
913	F	25	55.0	1.68
914	F	19	44.0	1.62
915	F	20	52.3	1.66

Table V.VI Demographic data of participants recruited in Chapter 10

	Sub ID	Age (yo)	Body weight (kg)	Body height (m)	BMI (kg/m2)
African elite runners	1011	37	53	1.67	19.1
	1012	29	51.3	1.67	18.6
	1013	26	58.5	1.71	20.0
	1014	33	55.8	1.67	20.0
	1015	35	54.2	1.70	18.8
African recreational runners	1021	29	54.5	1.66	20.0
	1022	32	51.6	1.66	18.7
	1023	28	60.7	1.73	20.3
	1024	27	60.1	1.80	18.5
	1025	28	92.1	1.90	25.6
Asian elite runners	1031	19	48.3	1.68	17.1
	1032	37	68.7	1.80	21.2
	1033	35	68.4	1.74	22.7
	1034	33	64.3	1.70	22.4
	1035	27	54	1.68	19.1
Asian recreational runners	1041	23	76.1	1.78	24.0
	1042	39	73.4	1.80	22.6
	1043	28	59.9	1.68	21.2
	1044	29	55.1	1.65	20.2
	1045	27	61.2	1.72	20.6

Table V.VII Demographic data of participants recruited in Chapter 11

Sub NO	Gender	Age (yo)	Body weight (kg)	Body height (m)
1101	F Fannie	36	62.3	1.67
1102	F Janet	24	46.4	1.61
1103	F Dorothy	21	52.2	1.57
1104	F Aislinn	22	62.2	1.76
1105	M Ivan	23	49.8	1.57

APPENDIX VI

Declaration of contributions of authorship

Title of the journal paper: Zhang JH, Chan ZYS, Au IPH, An WW, Shull PB, Cheung RTH. (2019) Transfer learning effects of biofeedback running retraining in untrained conditions. *Medicine & Science in Sports & Exercise* in-press

Zhang JH: Contributions to conception and design, acquisition of data, analysis and interpretation of data; drafting the article and revising it, and final approval of the version to be published

Chan ZYS: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Au IPH: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

An WW: Contributions to conception and design, analysis and interpretation of data, and final approval of the version to be published

Shull PB: Contributions to conception and design, revising the article critically for important intellectual content, and final approval of the version to be published

Cheung RTH: Contributions to conception and design, revising the article critically for important intellectual content, and final approval of the version to be published

Title of the journal paper: Zhang JH, Chan ZYS, Au IPH, An WW, Cheung RTH. (2019) Can runners maintain the newly learned gait pattern outside laboratory environment following gait retraining? *Gait & Posture*, 69: 8-11

Zhang JH: Contributions to conception and design, acquisition of data, analysis and interpretation of data; drafting the article and revising it, and final approval of the version to be published

Chan ZYS: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Au IPH: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

An WW: Contributions to conception and design, analysis and interpretation of data, and final approval of the version to be published

Cheung RTH: Contributions to conception and design, revising the article critically for important intellectual content, and final approval of the version to be published

Title of the journal paper: Zhang JH, McPhail AJC, An WW, Naqvi WM, Chan DLH, Au IPH, Luk ATW, Chen TLW, Cheung RTH. (2016) A new footwear technology to promote non-heelstrike landing and enhance running performance: Fact or fad? *Journal of Sports Sciences*, 35,15:1-5

Zhang JH: Contributions to conception and design, acquisition of data, analysis and interpretation of data; drafting the article and revising it, and final approval of the version to be published

McPhail AJC: Contributions to acquisition of data, acquisition of data, analysis and interpretation of data, and final approval of the version to be published

An WW: Contributions to conception and design, analysis and interpretation of data, revising the manuscript critically, and final approval of the version to be published

Naqvi WM: Contributions to acquisition of data, acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Chan DLH: Contributions to acquisition of data, acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Au IPH: Contributions to acquisition of data, acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Luk ATW: Contributions to acquisition of data, acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Chen TLW: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Cheung RTH: Contributions to conception and design, revising the article critically for important intellectual content, and final approval of the version to be published

Title of the journal paper: Zhang JH, An WW, Au IPH, Chen TL, Cheung RTH. (2016) 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

Zhang JH: Contributions to conception and design, acquisition of data, analysis and interpretation of data; drafting the article and revising it, and final approval of the version to be published

An WW: Contributions to conception and design, analysis and interpretation of data, and final approval of the version to be published

Au IPH: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Chen TLW: Contributions to acquisition of data, analysis and interpretation of data, and final approval of the version to be published

Cheung RTH: Contributions to conception and design, revising the article critically for important intellectual content, and final approval of the version to be published