EFFECTS OF WINDLASS ENHANCING FEATURE ON KINEMATICS AND KINETICS DURING PROPULSIVE STANCE PHASE OF RUNNING

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Abstract

The purpose of this study was to investigate and compare the range of motion changes and force production for running footwear with and without windlass enhancing feature, and barefoot, on the lower extremities during late stance phase of running. Fourteen healthy recreational rearfoot male runners (age 20.14+0.66 years, height 171.79+4.66 cm, and body weight 64.56+5.79 kg.) were recruited. Three-dimensional movement analysis and force production were collected by a motion analysis system and AMTI force platform, and the data were calculated and analysed by Visual 3D. The participants, barefoot and two types of footwear, namely running footwear with and without windlass enhancing feature, started to run along the runway with speed at 3.5 m/s (range between 3.33-3.68 m/s) for three trials in each condition. The repeated measures analysis of variance was used for analysis. A Bonferroni post hoc test was conducted between conditions ($p < .01$). The results revealed that the ankle movement barefoot and with the running footwear without windlass enhancing feature were significantly different from the running footwear with the windlass enhancing feature at the beginning, but that of barefoot was significantly different from the running footwear with and without windlass enhancing feature at the end of the late stance phase. The forefoot's range of motion barefoot and with the running footwear without windlass enhancing feature was significantly different from the running footwear with the windlass enhancing feature, but the vertical ground reaction forces of the running footwear with and without windlass enhancing feature were not significantly different. Significant difference was found between barefoot and running footwear with the windlass enhancing feature in force production. In conclusion, the running footwear without windlass enhancing feature offers more flexible forefoot movements, close to barefoot, but the propulsion is still the same as the running footwear with the windlass enhancing feature.

Keywords: Windlass enhancing feature, Running, Propulsive stance phase

Introduction

Humans have engaged in endurance running for millions of years either barefoot or with minimal footwear such as sandals or moccasins (Bramble and Lieberman, 2004). Nowadays, millions of people are involved in recreational running all over the world. Running is one of the most popular forms of aerobic exercises, as it requires no membership, is inexpensive and offers numerous health benefits (Dugan and Bhat, 2005; Hafstad et al., 2009). Running can be seen as a series of alternating hops from left to right leg. The running cycle is composed of a stance phase, in which one foot is in contact with the ground while the other foot is swinging in the air, followed by a flight phase where both legs are off the ground. Running generates a complex, dynamic set of forces which are repeated with every step. The foot strikes the ground approximately 600 times per mile, absorbing more than 3 to 4 times body weight (Lieberman et al., 2010). As the foot progresses through the stance phase just before toe-off, the metatarsophalangeal joints (MTPJs) become rigid as they extend in preparation to push off the ground for the propulsion and thrust the body forward. Based on this information, it would be logical for a runner to wear footwear that would be able to absorb more vertical ground reaction force (VGRF). The VGRF is principally transmitted through the subtalar skeleton, with peak forces at heel-strike through calcaneus and at heel-off through the MTPJs. The resultant forces through the foot are principally altered by any elasticity in the footwear and minor changes in foot position constrained by the footwear (Burnfield, Few, Mohamed & Perry, 2004).

Since humans use footwear for thermal protection in climate conditions and mechanical protection during activities in all environments and terrains, the design of footwear has varied enormously through time and from culture to culture, with appearance originally being tied to function. Contemporary footwear varies widely in style, function, complexity and cost. Not only footwear plays a fundamental role in the protection of the foot from heat, cold, and damage caused by direct contact but also prevents injuries by absorbing the ground impact while walking or running and reducing fatigue of the foot and lower extremity, and offer increased stability (Landry, Nigg, & Tecante; 2010). Most types of footwear are designed for specific activities. Athletic footwear is specifically designed to be worn when participating in various sports. Modern running footwear is a type of athletic footwear which dates back to the 1970s. By the early 1900s, sneakers or all-purpose athletic footwear were being produced by small rubber companies. As the 1920s and 1930s approached, the footwear manufacturers started marketing footwear for different sports. Contemporary footwear designers focus on the anatomy and the movement of the foot. Limb movement, the effect of different terrains on impact, and foot position on impact has been analysed. Athletic footwear is constructed on two principles: the improvement of performance and the prevention of excessive load and related injuries. Major athletic footwear manufacturers have generally responded to new knowledge about running injuries and injury mechanisms, which reported the prevalence rates from 19.4% to 79.3% in musculoskeletal injuries during running, by introducing new designs and components intended to make their products more functional (Van Middelkoop, Kolkmon, Van Ochten, Bierma-Zeinstra & Koes, 2008a; Van Gent et al., 2007).

The windlass enhancing feature or toe spring, another major design feature, has been built into most conventional footwear including the athletic footwear, refers to the gradual increase in the elevation of the sole of the shoe off a flat surface from the ball region to the tip of the shoe. This feature causes a slight dorsiflexion of the MTPJs, resulting in reducing dorsiflexion of the MTPJs during the push-off phase and facilitating rolling of the body over the ground, and reducing the need for movement in the foot (Hansen & Wang, 2010). The windlass enhancing feature creates a rocker effect on the shoe sole so that the shoe, instead of full flexing as it should, forcing the foot to "roll" forward at the end of the stride like the curved bottom of a rocking chair and helping facilitate a heel strike. The assumption is that the sole curvature facilitates rolling of the body over the ground reducing the need for movement in the foot. The modern running footwear is designed with a windlass enhancing feature in order to facilitate toe off and helps reducing forefoot plantar pressure. The thicker the sole, such as on sneakers or boots, or the stiffer the sole, the greater windlass enhancing feature needed because of lack of shoe flexibility. The previous studies showed that the ankle was less plantar-flexed (Boyer & Andriacchi, 2009) and the VGRF significantly decreased in the late stance phase (Taniguchi, Tateuchi, Takeoka & Ichihashi, 2012). In addition, footwear with a curved “rollover” sole are prescribed for those who would benefit from reduced motion in the foot (Hutchins, Bowker, Geary & Richards, 2009). Previous studies have investigated the rollover effect only in special footwear such as MBT footwear, which is characterized by a rounded sole, but there has been no evidence of the study of the kinematics and kinetics in the commercial athletic footwear. Recently, questions have arisen concerning whether the windlass enhancing feature is essential for footwear. This study concerns the biomechanical aspects of the running footwear with windlass (RW) and non-windlass enhancing features (RNW) which is to investigate and compare the range of motion (ROM) changes and force production of the RW, RNW and barefoot (BF) on non-dominant’s lower extremity during late stance phase of running.

Methods

Participants

The participants in the study were fourteen healthy recreational rearfoot male runners with a mean age of 20.14+0.66 years, a mean height of 171.79+4.66 cm, and a mean weight of 64.56+5.79 kg. The inclusion criteria for the study included 16 km or more distance of running per week (10 miles or more per week), three times or more per week (Glover & Glover, 1999), normal 1st metatarsophalangeal joint range of motion (> 90o) (Hopson, McPoil, & Cornwall, 1995), an arch height index (AHI) in the range of 0.35-0.38 (Roy, Bhattacharya, Deb & Ray, 2012) and a leg length discrepancy less than 1 cm (O'Connor & Wilder, 2001). Participants who reported any history of fracture or surgery to either lower extremity, a history or physical findings of any trunk, back or foot pain, foot or traumatic deformities to either lower extremity, especially to the ankle, foot or any acute symptoms of lower extremities injury 6 months prior to data collection, were excluded from the study. One group with three replications was compared and had been reasoned to expect a "large" effect size (f = .40) (Cohen, 1988). This study received ethics clearance from the Mahidol University Institutional Review (MU-IRB) No. 2014/059.3004 prior to participated recruitment. All participants were informed about the purposes, procedures and advantages of the study, and consent forms were signed prior to starting the experimental procedures. The study was conducted at Motion analysis laboratory, Siriraj hospital, Mahidol University.

Procedures

Anthropometrics, including body weight, height, leg length, and range of motion (ROM) of lower extremities were measured and recorded for each participant. The participants performed a short warm-up protocol consisting of static stretching and continuous aerobic running at a self-selected comfortable pace that would be similar to a pace that they would use along a runway for 5 minutes to ensure they were comfortable with the protocol before beginning data collection (Takizawa, Yamaguchi, & Shibata, 2015). The participants were asked not to look down at the runway while practicing and were constantly observed by the investigator during the practice period. Following the warm-up, the participants were fitted with 40 reflective markers placed over following landmarks according to Plug-In Gait Model and Oxford Foot Model on both legs and feet. Static and dynamic calibrations were recorded by 3D Motion analysis system (Motion Analysis Corp., US) with 8 infrared cameras. Cortex 3.0 software was used for collecting the temporospatial data and VGRF data originated by the AMTI Force platform (AMTI, Ltd., US). The force platform gain was set to as per the recommendations and calibrated on installation by the manufacturer. It was embedded into the middle of the long runway and was oriented lengthwise in the running direction along the track. The force data were sampled at 1600 Hz, with a low-pass Butterworth filter being applied following each trial.

The participants were required to run at a controlled speed of 3.5 meters per second within 5% accuracy (range between 3.33-3.68 m/s) (Divert, Mornieux, Baur, Mayer & Belli, 2005) and landed on their non-dominant foot in the middle of a force plate. Running speed was monitored with two pairs of Speedlight timing systems (Swift Performance Equipment, US) placed 2.5m before and after the force platform. All participants performed three trials of rearfoot strike running across a force platform in each of three different conditions; barefoot (BF), running footwear with the windlass enhancing feature (RW), and footwear with non-windlass enhancing feature (RNW). Running footwear were the same for all subjects but differ in size and were considered windlass enhancing (Reebok, VERSA TRAIN 2.0) and non-windlass enhancing features (Vibram Five Fingers, SEEYA); size between 7-10 of UK system. The VGRF was collected via a force plate to synchronized with kinematic data and were used to determine the MTPJ angle and VGRF to the last 40% stance phase (Giddings, Beaupre, Whalen & Carter, 2000), and imported to Visual3D (C-motion, Inc., US) to analyse the measuring kinematic and kinetic data. The order of presentation of the conditions was randomly selected as show in Table 1. The subjects were instructed to perform three successful trials. Between each condition, the subjects were allowed a minimum of 5 minutes of rest.

Table 1: Randomized order of measurements

Replication	1st measurement	2nd measurement	3rd measurement
1st replication	BF	RW	RNW
2nd replication	BF	RNW	RW
3rd replication	RW	BF	RNW
4th replication	RNW	BF	RW
5th replication	RW	RNW	BF
6th replication	RNW	RW	BF

Statistical analysis

The descriptive statistics of means and standard deviations were used to describe the outcome measures and the characteristics of subjects such as age, height, body weight. The distribution of normality was examined with the Shapiro-Wilk test. The differences between ROM of non-dominant's lower extremity and kinetic force production during last 40% of running stance phase, which were extracted for statistical analysis, analysed by repeated measures Analysis of variance (ANOVA). A Bonferroni post hoc test was conducted between footwear conditions. All statistical analyses in the research were conducted using a statistical software for data analysis with statistical significance accepted at the $p < 0.05$ level.

Results

The experimental research objectives were to investigate and compare the ROM changes and force production of the RW, RNW and BF on non-dominant's lower extremity during late stance phase of running. The mean values of the ROM of non-dominant's lower extremity are presented in Table 2.

Table 2: The mean ROM of lower extremity throughout the late stance phase.

Joints	BF	RW	RNW
Hip	9.62^0 of flexion – 11.60^0 of extension	10.35^0 of flexion – 10.53^0 of extension	9.55^0 of flexion – 10.55^0 of extension
Knee	30.86^0 – 16.14^0 of flexion	30.67^0 – 17.22^0 of flexion	31.51^0 – 11.92^0 of flexion
Ankle	21.27^0 of dorsiflexion – 31.01^0 of plantarflexion	14.61^0 of dorsiflexion – 23.75^0 of plantarflexion	24.36^0 of dorsiflexion – 23.66^0 of plantarflexion
MTP	10.67^0 – 8.6^0 of flexion	30.67^0 – 28.28^0 of extension	6.78^0 – 11.79^0 of flexion

This indicates that the movements of the hip and knee throughout the late stance phase was significantly different. The movements of ankle in BF and RNW were similar at the beginning of the phase and significantly different from RW, but the movement of BF was significantly different from RW and RNW at the end of the phase. The results of the ANOVA indicated significant time effect from the 61st to 100th percent time cycle, with Wilks' Lambda = 0.649, $F(2, 12) = 5.724$, $p < .05$, $\eta^2 = 0.278$. Each pairwise difference indicated that BF and RNW were similar at the beginning of the phase and significantly different from RW at the 61st - 66th percent time cycle and BF was significantly different from RW and RNW at the 83rd - 100th (Figure 1).

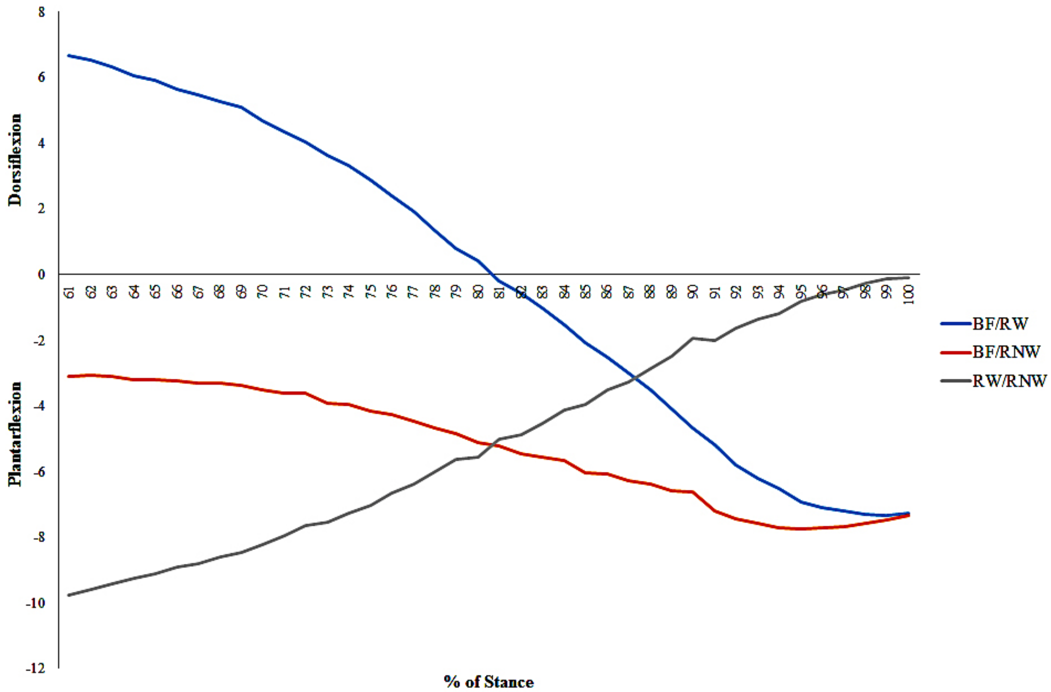

Figure 1: Mean differences of the ROM of the ankle joint at the 61st to 100th percent time cycle of the non-dominant lower extremity between 1) BF and RW, 2) BF and RNW, and 3) RW and RNW.

In addition, there was clear evidence that the MTPJ in RW was limited in hyperextension by the footwear shape. The results of the ANOVA indicated significant time effect from the 61st to 100th percent time cycle, Wilks' Lambda = 0.327, $F(2, 12) = 20.628$, $p < .01$, $\eta^2 = 0.648$. Each pairwise difference indicated that BF significantly differed from RW and from RNW at the 61st - 100th percent time cycle (Figure 2).

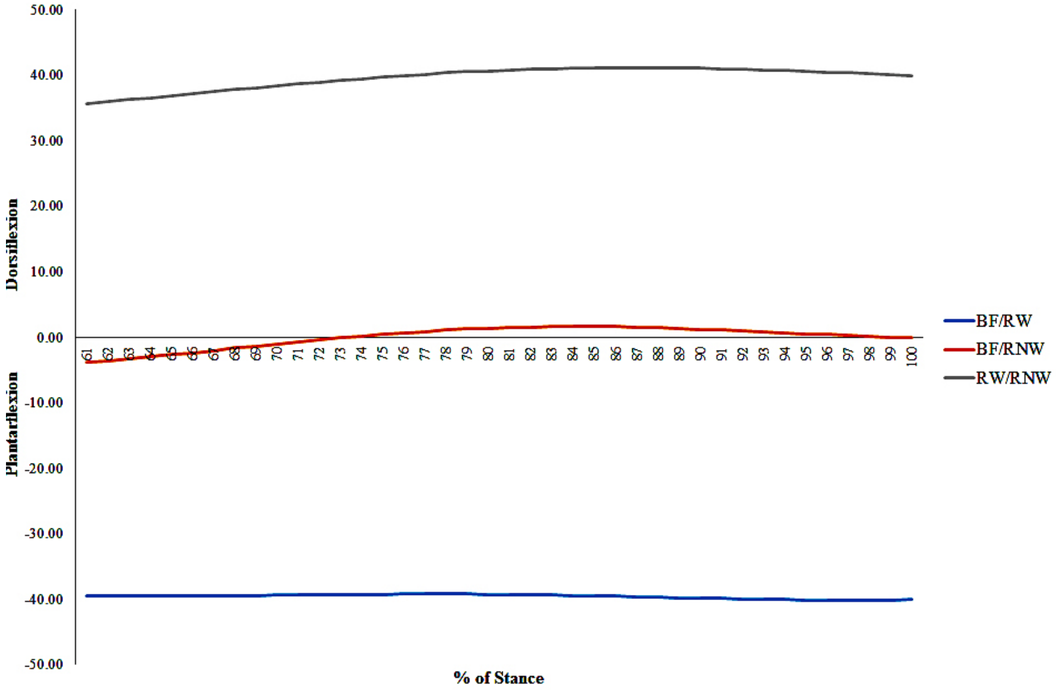

Figure 2: Mean differences of the ROM of the 1st MTPJ at the 61st to 100th percent time cycle of the non-dominant lower extremity between 1) BF and RW, 2) BF and RNW, and 3) RW and RNW.

The mean values of the VGRF per body weight of the non-dominant lower extremity at the 61st - 100th percent time cycle declined from 1.97 to 0.668 in BF, 1.91 to 0.674 in RNW and 1.87 to 0.676 in RW (Figure 3). The results of the ANOVA indicated time effect from the 62nd to 86th percent time cycle, Wilks' Lambda = 0.998, $F(2, 12) = 5.328$, $p < .05$, $\eta^2 = 0.489$. Each pairwise difference indicated that BF were significantly different from RW from the 61st to 84th percent time cycle and significantly different from the RNW from the 64th to 84th percent time cycle (Figure 3).

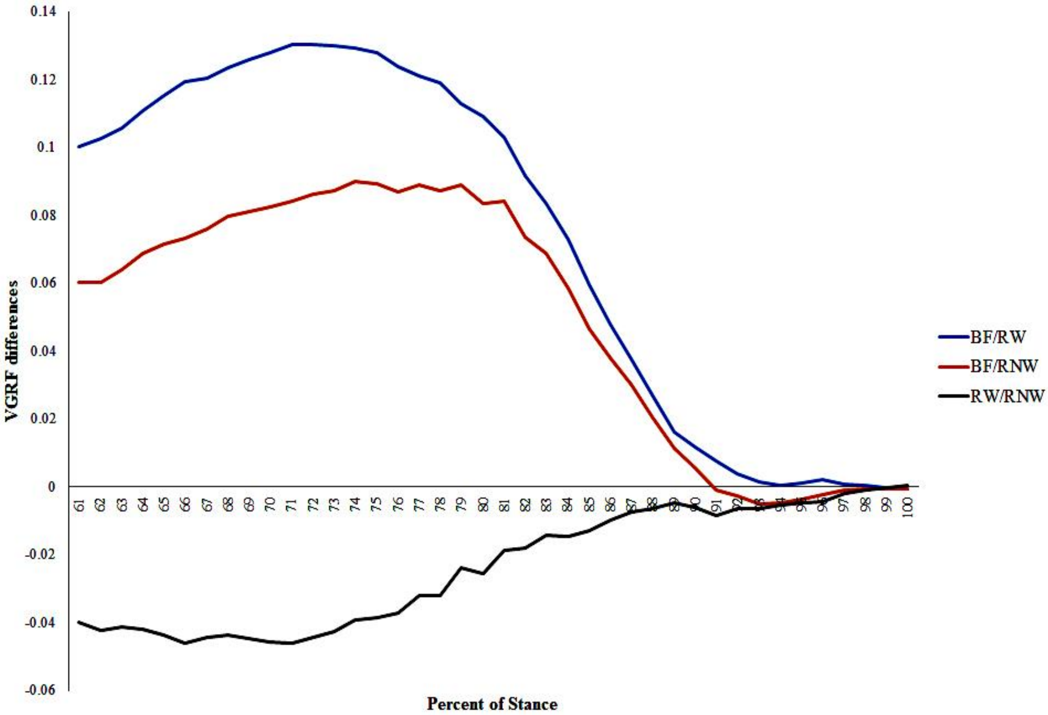

Figure 3: Mean differences of VGRF at the 61st to 100th percent time cycle of the non-dominant lower extremity between 1) BF and RW, 2) BF and RNW, and 3) RW and RNW.

Discussion

The purpose of the study was to investigate and compare the ROM changes and force production of the RW, RNW and BF on non-dominant's lower extremities in the late stance phase of running. The sagittal plane movement patterns of lower extremities continue from midstance, as the function of force generation, to toe-off. In the present study, Lt. ankle joint kinematics of the BF and RNW at the beginning dorsiflexed more than the RW, and of the BF at the end plantarflexed more than the RW and RNW ($p < .05$). The differences of the surface hardness and shape of footwear require the adaptations of lower extremities. The changes in sagittal plane have been found in several research (Dixon, Collop & Batt, 2000; Hardin, Van Den Bogert & Hamill, 2004; Boyer and Andriacchi, 2009). According to the previous study, ankle adaptations were found. The ankle joint increased plantarflexion at toe-off (Keenan, Franz, Dicharry, Della Croce & Kerrigan, 2011). In addition, the traditional footwear with rigid shape requires less gait modification than that of minimalist footwear or barefoot. The MTPJ movement pattern revealed significantly higher plantarflexion of the BF and RNW than of the RW throughout the late stance phase ($p < .01$). The results of this study corresponded with those of previous studies which suggested the footwear with rigid windlass enhancing feature has effect in reducing the MTPJ's plantarflexion during push-off or late stance as compared with other footwear (Hutchins et al., 2009; Csapo, Maganaris, Seynnes & Narici, 2010; Cronin, Barrett & Carty, 2012; Lin et al., 2013; Chen, Tu, Liu & Shiang, 2014). The windlass enhancing feature refers to the elevation of footwear's toe box above the ground or supporting surface that allow the toe in dorsiflexion position. Most types of footwear design in the footwear market appear to have at least some degree of toe spring or windlass enhancing feature. There are questions about the need and the mechanism of the windlass enhancing feature on running gait. According to Hick's model of windlass effect (Hick, 1954), this feature makes plantar fascia wound around the metatarsal head. This winding shortens the distance between metatarsals and calcaneus, then the medial longitudinal arch is elevated. This windlass mechanism occurs during the push-off or late stance phase (Leardini et al., 2007), makes the foot more stiffness to form a rigid lever for propulsion to overcome the force and friction and potentially propel the body forward in running (Hick, 1954; Arndt et al., 2013). Although this feature enhances comfort, it may potentially restrict the motion of the forefoot and interfere with the normal function of the arch to act as spring and shock absorber.

While running, the connective tissues such as ligaments, tendons, and muscles of the lower extremities store elastic energy in the first half and recoil in the late stance phase. The propulsion begins as the heel lifts of the ground. This serves to accelerate the body's CG upward and forward throughout the swing phase. The 3rd rocker during the heel rising begins to generate power and the metatarsal heads serve as axis of rotation. There were evidences that this propulsive force increases (Boyer & Andriacchi, 2009; Keenan et al, 2011; Perl, Daoud & Lieberman, 2012; Zhang, Paquette & Zhang, 2013). For this hypothesis, the results of the study revealed that the VGRF of BF was the greatest whereas of the RW is the lowest. This finding corresponded with other previous studies that the VGRF was statistically lower in the footwear with forefoot rolling or windlass enhancing feature than barefoot, both immediately or after familiarizing with the footwear (Zhang et al., 2012; Cham & Safaeepour, 2015; Deneweth, McGinnis, Zernicke & Goulet, 2015). The windlass enhancing feature generally elevates the forefoot at least 15 degrees above the ground, creates a rocker mechanism for assisting the 3rd rocker function at MTPJs to roll the body weight over and toe off more rapidly by facilitating the forward advancement of the tibia over the foot, where the ankle joint is restricted in the sagittal plane (Wu, Rosenbaum & Su, 2004; Perry, 2010).

The MTPJ in greater dorsiflexion, when the CG shifts to the forefoot during late stance and the impact force occurs, leads to greater force production to push the CG forward and upward in BF as well as RNW (Miller, Whitcome, Leiberman, Norton & Dyer, 2014). Our results found that even though the sagittal plan motion of RNW was significantly different from RW, there was no significant difference in the VGRF. The results of this study were the acute effect. Even when the participants were familiarized by running with the footwear before the test for a while, adaptation was still required. There are several incidences stated about the transition process from conventional running footwear to minimalist footwear. This process gradually lasts from minimal of a few weeks to several months up to individuals (Hart & Smith, 2008; Rixe, Gallo & Silvis, 2012; Rothschild, 2012; Giandolini, Horvais, Farges, Samozino & Morin, 2013; Fuller, Thewlis, Tsiros, Brown & Buckley, 2015; Chen, Sze, Davis & Cheung, 2016). The results of this study suggested the need for additional studies on the effects of RNW on foot production after transition process from conventional running footwear to minimalist footwear. It would be beneficial for understanding and improving the pattern of movement in order to prevent injury.

Conclusion

In summary, the propulsive force was still the same as the RW, even with the structure of the RNW, which is more flexible and gives the forefoot the freedom to move. This could offer more flexible forefoot's movements close to the barefoot in the late stance phase. Future research should focus on the transition period from conventional running footwear to minimalist footwear to obtain a better understanding the mechanism of loading to the forefoot during late stance phase.

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