EFFECTS OF FOOTWEAR AND RUNNING SPEED ON FOOT KINEMATICS IN THE FRONTAL PLANE

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Excessive foot motion and increased running speed are frequently discussed as injury inducing factors in runners. We assessed foot kinematics using an inertial measurement unit while subjects ran at different running speeds wearing varying shoes. 20 male runners ran at 2.9, 3.5, 4.2 m/s wearing an all-purpose shoe (NS) and two differently configured running shoes: high arch support, wedges, soft damping (Con1) and low arch support, no wedges, hard damping (Con2). Maximum pronation velocity was higher when running in NS than in Con1 ($p = 0.03$) and when running at higher speeds ($p < 0.01$). Subjects showed increased ROM when wearing NS compared to Con1 ($p < 0.01$) or Con2 ($p = 0.04$) and at higher speeds ($p < 0.01$). As shoe variations and running speed led to changed kinematics, these parameters should be considered when investigating biomechanical parameters.

KEY WORDS: motion control shoes, running speed, biomechanics, shoe modifications, foot motion inertial measurement unit.

INTRODUCTION: Running is one of the most common physical activities spent during leisure time. The number of participants in marathon runs has increased from 25 000 in 1976 to 541 000 in 2013 in the US alone (Lamppa, 2014). Besides its positive health effects, running may also cause acute or chronic injuries (Schueller-Weidekamm, 2010). Excessive motion of the rearfoot is frequently suggested as an injury inducing factor (Messier & Pittala, 1988). Foot eversion is coupled with internal tibial rotation and may cause overloading at the knee joint (Hintermann & Nigg, 1998). Rodrigues, TenBroek, & Hamill (2013) state that runners with anterior knee pain (AKP) use a greater amount of their passive pronation range of motion (ROM) while Nielsen et al. (2014) found overuse injuries not to be related to foot pronation. However, the latter used the Foot Posture Index to categorize study participants into groups according to their static foot posture, not examining dynamic motion in the frontal plane. Shoe modifications are used to influence foot kinematics, aiming at injury prevention. An influence on foot kinematics by reducing peak eversion (Rodrigues, Chang, TenBroek, & Hamill, 2013), peak eversion velocity and ROM (Rodrigues, Chang, et al., 2013) could be proven. In a large meta-analysis Cheung, Chung, & Ng (2011) found running shoes with medial wedges or heel flare to be more effective in controlling eversion than those with dual midsole materials. Nevertheless, high inter-subject variability in rearfoot kinematics and therefore diverse effects of different shoe sole constructions were proven (Stacoff et al., 2001). Running speed is frequently discussed as an injury inducing factor. De David, Carpes, & Stefanyshyn (2014) found joint loading of the ankle and knee to increase with increasing running speed. Higher peak moments may lead to harmful loading of these structures. To our knowledge, no study has yet investigated the dependency of shoe modification effects on different running speeds. An easy to use tool is needed to assess individual kinematic responses to differences in footwear in the field. A modular running shoe system with a multitude of possible configurations may be a useful appliance when testing a runner's response to variations in footwear. Therefore, the goal of the present study was to determine foot kinematics at different running speeds using an inertial measurement unit (IMU) while wearing two differently configured running shoes as well as a neutral all-purpose shoe. Decreased ROM and maximum pronation velocity (MaxProVel) were hypothesized to occur when running in shoes that are equipped with motion control components. As these shoes aim at limiting foot kinematics in the frontal plane, we hypothesized the final pronation following initial contact to occur earlier than in the neutral all-purpose shoe. Previous research showed increased ankle joint excursion with increasing running speed in barefoot runners (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006). We therefore expected to find an increase in ROM and MaxProVel at higher running.

METHODS: Twenty male rearfoot runners participated in this study (age: 22.5 ± 1.4 years; running distance per week: 19.4 ± 10.5 km). Measurements were performed with subjects running at 2.9, 3.5 and 4.2 m/s on a treadmill (Woodway ERGO XELG 90®, Woodway USA Inc.) while wearing two different running shoe configurations as well as a neutral all-purpose shoe (NS; Adidas Gazelle®, Adidas). A modular running shoe (Runaissance 3.0®, Newline) was used to provide two different configurations: one with high arch support, medial wedges (4 mm) and soft damping material (Con1), the other with low arch support, no medial wedges and hard damping material (Con2). All shoes were tested according to ASTM F-1976 standards (see table 1).

Table 1: Damping characteristics of shoe configurations used in the present study.

Shoe	Maximum Force [N]	G-Score (Peak)	Peak-to-peak ratio [%]
Con1	867,3	14,3	55,6
Con2	914,9	15,6	55,5
NS	1546,5	24,1	50,7

An IMU was firmly attached to the heel cap of each of the right shoes. Data of the IMU were recorded at 3000 Hz using Noraxon Telemyo 2400 G2 (Noraxon Corporate, USA). An insole plantar pressure system (F-Scan®, Tekscan Inc.) was used to allow for step detection. Foot kinematics were evaluated in the frontal plane during stance phase. Acceleration data were low pass filtered to remove gravitational influence. Then, acceleration and gyroscope data were combined with a complementary filter and integrated to get movement angles of the IMU. Angles obtained from the IMU were compared to movement angles obtained with a commercial movement analysis system (XSens MTw®). Motions in the frontal plane will further be denoted as pronation and supination although it should be noted that in this study they do not describe motions of the rearfoot relative to the tibia. Maximum pronation (MaxPro), MaxProVel, ROM in the frontal plane as well as time to final pronation following initial contact (TFPro) were used as dependent variables. To determine if there were significant differences in the dependent variables between shoe conditions or running speeds two-way repeated measures ANOVAs were performed. Separate ANOVAs were run for each dependent variable. Post hoc tests were performed using modified t-tests with Bonferroni correction. All statistical calculations were completed using SPSS (SPSS 21, IBM) and the alpha-level was set at 0.05.

RESULTS:

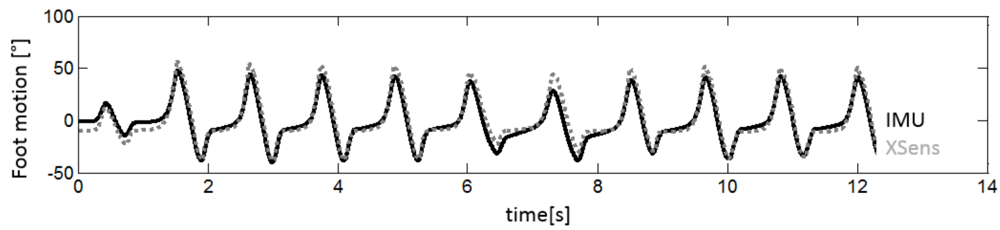

Figure 1: Data obtained synchronously with the IMU used in the present study and with the commercial XSens system.

Movement angles obtained from the IMU were in agreement with those obtained with the commercial XSens system (figure 1). All results of MaxProVel are presented in degrees per second [°/s]. Significant main effects were found for configuration ($p = 0.04$) and running speed ($p < 0.01$). A mean increase of 30.5 was found in MaxProVel while running in NS (132.9 ± 140.3) compared to Con1 (102.4 ± 108.5; $p = 0.03$). MaxProVel also differed significantly between running at 2.9 m/s (102.2 ± 108.1) and running at 4.2 m/s (138.7 ± 139.6; $p < 0.01$). All ROM values are presented in degrees [°]. Significant main effects were found for configuration ($p < 0.01$) and running speed ($p < 0.01$). Subjects showed a significantly higher ROM while running in NS (5.6 ± 4.9) compared to running in Con1 (4.3 ± 4.3; $p < 0.01$) or Con2 (4.8 ± 4.7; $p = 0.04$). An increase in ROM could also be observed at 4.2 m/s (5.2 ± 5.3) compared to 2.9 m/s (4.5 ± 4.4; $p < 0.01$) as shown in figure 2. None of the investigated comparisons revealed a significant difference in TFPro between different shoe configurations ($p = 0.40$) or running speeds ($p = 0.40$). Also, MaxPro did not differ when varying shoe conditions ($p = 0.86$) or speed ($p = 0.63$).

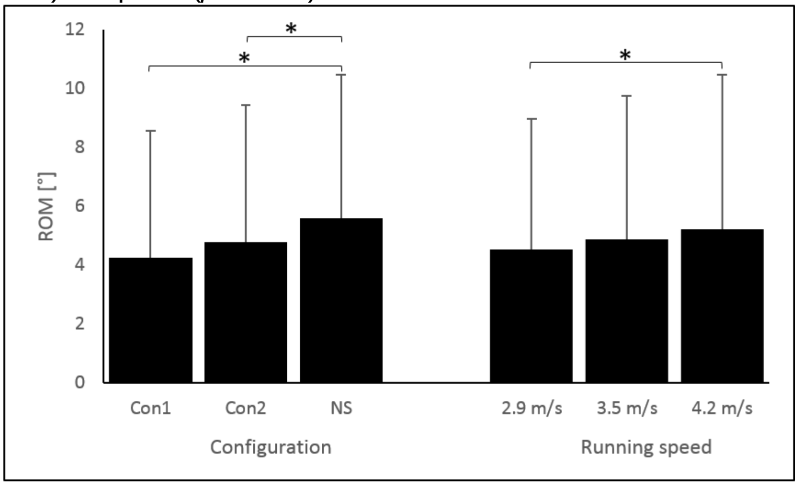

Figure 2: ROM averaged over shoe conditions as well as over running speeds. Stars indicate significant differences (p < 0.05), error bars represent SDs.

DISCUSSION: The goal of the present study was to determine foot kinematics at different running speeds using an IMU while wearing different running shoes. The ROM found in the present study is comparable to previous findings (Peltz et al. 2014). It should be noted however, that in the present study foot motions were not measured relative to the tibia but a quantification of roll dynamics of the foot was performed. If motions are determined relative to the tibia, increased ROM may be detected due to movements of the lower leg during the stance phase with the foot itself being stationary. We found reduced ROM when subjects wore Con1 or Con2 compared to NS. Therefore, shoes with harder damping material resulted in increased ROM of the foot. Together with knee flexion, pronation is known to function as a damper of impact forces. Shoes with harder damping will forward higher impact loading to the body. Therefore increased ROM may display a technique to limit impact forces to a bearable, non-harmful amount. A significant decrease in MaxProVel could be proven when running in Con1 compared to NS. This is in agreement with the findings of Brown, Donatelli, & Catlin (1995) who found MaxProVel to be lower while walking with arch supports. It should be noted though, that we found a dependency of MaxProVel on running velocity. Therefore MaxProVel is expected to be lower during walking compared to running. The comparability of these results may have been caused by the neglected relative motion of the foot inside the shoe. MaxProVel measured directly on the foot may have been even higher in the present study.
Accelerated running speed led to increased ROM and MaxProVel as we hypothesized. The simultaneous increase of these parameters is in agreement with the findings of Shih, Ho, & Shiang (2014). Running speed therefore not only influences joint loading but also foot kinematics. Interestingly, no interaction effect of speed*condition was found in the present study. Therefore running speed did not influence the effects of modified shoes on foot kinematics. Findings from previous studies on shoe modifications which were conducted at different running speeds may consequently be compared.
We analysed motions of the foot in the frontal plane using a single IMU. Whether these findings can be compared to data obtained from models accounting for motions of the foot segment relative the tibia remains to be analyzed in more detail. Also, relative motions of the foot inside

the shoe take place during running. It should therefore be considered that the movements of the foot might be different than the data obtained on the outside of the shoe.

CONCLUSION: In conclusion, the IMU which was used as a measurement tool proofed to be a useful method when quantifying foot kinematics during running. The modular running shoe system may provide first insights on how individuals react to shoe modifications as it lead to changed kinematics. Both, running shoe modifications as well as differences in running speed led to changes in ROM and MaxProVel. Future studies should therefore consider these factors as possibly influencing the mechanisms of overuse injuries.

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REFERENCES:
Bishop, M., Fiolkowski, P., Conrad, B., Brunt, D., & Horodyski, M. (2006). Athletic Footwear, Leg Stiffness, and Running Kinematics. *Journal of Athletic Training*, *41*(4), 387–392.
Brown, G. P., Donatelli, R., & Catlin, P. A. (1995). The Effect of Two Types of Foot Orthoses on Rearfoot Mechanics. *Journal of Orthopaedic & Sports Physical Therapy*, *21*(5), 258–267.
Cheung, R., Chung, R., & Ng, G. (2011). Efficacies of different external controls for excessive foot pronation: a meta-analysis. *British Journal of Sports Medicine*, *45*(9), 743–51.
De David, A., Carpes, F., & Stefanyshyn, D. (2014). Effects of changing speed on knee and ankle joint load during walking and running. *Journal of Sports Sciences*, *8*, 1–7.
Hintermann, B., & Nigg, B. M. (1998). Pronation in Runners. *Sports Medicine*, *26*(3), 169–176.
Hreljac, A. (2005). Etiology, prevention, and early intervention of overuse injuries in runners: A biomechanical perspective. *Physical Medicine and Rehabilitation Clinics of North America*, *16*, 651–667.
Kersting, U., & Brüggemann, G. (2006). Midsole material-related force control during heel-toe running. *Research in Sports Medicine*, *14*(1), 1–17.
Lamppa, R. (2014). 2014 Annual Marathon Report. Retrieved from http://www.runningusa.org/index.cfm?fuseaction=news.details&ArticleId=332
Messier, S. P., & Pittala, K. A. (1988). Etiologic factors associated with selected running injuries. *Medicine and Science in Sports and Exercise*, *20*(5), 501–5.
Nielsen, R. O., Buist, I., Parner, E. T., Nohr, E. A., Sorens, H., Lind, M., & Rasmussen, S. (2014). Foot pronation is not associated with increased injury risk in novice runners wearing a neutral shoe: a 1 year prospective cohort study. *British Journal of Sports Medicine*, *48*, 440–447.
Peltz, C. D., Haladik, J. a, Hoffman, S. E., McDonald, M., Ramo, N. L., Divine, G., … Bey, M. J. (2014). Effects of footwear on three-dimensional tibiotalar and subtalar joint motion during running. *Journal of Biomechanics*, *47*(11), 2647–53.
Rodrigues, P., Chang, R., TenBroek, T., & Hamill, J. (2013). Medially posted insoles consistently influence foot pronation in runners with and without anterior knee pain. *Gait & Posture*, *37*(4), 526–531.
Rodrigues, P., TenBroek, T., & Hamill, J. (2013). Runners with anterior knee pain utilize a greater percentage of their available pronation range of motion. *Journal of Applied Biomechanics*, *29*(2), 141–6.
Schueller-Weidekamm, C. (2010). Long-term success and risk for marathon runners. *Der Radiologe*, *50*(5), 444–52.
Shih, Y., Ho, C., & Shiang, T. (2014). Measuring kinematic changes of the foot using a gyro sensor during intense running. *Journal of Sports Sciences*, *32*(6), 550–6.
Stacoff, A., Reinschmidt, C., Nigg, B. M., van den Bogert, A. J., Lundberg, A., Denoth, J., & Stüssi, E. (2001). Effects of shoe sole construction on skeletal motion during running. *Medicine & Science in Sports & Exercise*, *33*(2), 311–319.