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Research article

Lower Extremity Support Moment and Distribution of Joint Moments during Sloped Running

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Abstract

The existing literature often exhibits inconsistent findings regarding lower extremity kinetics during sloped running, likely due to high variability of typical individual joint moments between and within runners. A better understanding of the kinetic effects of sloped running may be achieved by comparing the support moment and joint contributions among level, upslope, and downslope running. Twenty recreational runners (10 females) ran on three different conditions (level, 6° upslope and 6° downslope). Total support moment and joint contributions of the hip, knee, and ankle joints were compared among the three slope conditions using a one-way ANOVA with repeated measures and post-hoc pairwise comparisons. Our results showed that peak total support moment was highest during upslope running and was lowest during downslope running. The joint contribution to total support moment was similar in upslope and level running where the ankle joint has highest contribution followed by the knee and hip joints. During downslope running, highest knee joint contribution but least ankle and hip joint contributions were found when compared to level and upslope running.

Key words: Downslope, injuries, joint contribution, level running, kinetics, upslope.

Introduction

Running is a popular exercise for fitness and recreational purposes. While most of the running studies focus on running on level surface, runners inevitably run on various sloped surfaces especially during trail running and ultra-marathon races (Vernillo et al., 2017). Runners experience different task demands from biomechanical, physiological and neuromuscular aspects during sloped running compare to level running (Vernillo et al., 2017).

Previous studies showed that runners change their step frequency, step length, lower extremity energetics, and joint moments to adapt to upslope or downslope running surfaces (Roberts and Belliveau, 2005; DeVita et al., 2008; Telhan et al., 2010; García-Pinillos et al., 2019; Park et al., 2019). Specific to individual lower extremity joint moments, inconsistent findings have been reported from different studies. Telhan et al. (2010) reported that moderate changes in the slope (4º upslope and downslope) caused only minimal changes in ankle, knee and hip joint moments during running. On the contrary, Park et al. (2019) found runners exhibited greater knee moment and reduced ankle moment when running at 9º downslope compared to level running. Roberts and Belliveau (2005) demonstrated an increase in the hip moment and a decrease in the knee moment during a 12º upslope running compared to level running while the ankle moment was independent to the slope conditions. Among the aforementioned studies, no study has compared joint moments during all three running conditions (upslope, level and downslope) at once. In addition, Devita and Skelly (1990) has raised the concern of high intra-subject variability of individual joint moment data during running, which may be a potential factor for the aforementioned inconsistent finding. From Devita and Skelly's results, a relatively low variability in total support moment was reported during level running. Limitation from previous studies also include the small sample sizes (only 4 runners in Roberts and Belliveau 2005's work), and sex differences (only male runners were recruited in the studies of Park et al., 2019 and Roberts and Belliveau, 2005). Therefore, there is a need to investigate the effects of the three different slopes (upslope, level and downslope) on the kinetic profile of lower extremity of both female and male runners with the analyses of support moment.

The concept of support moment was first described by Winter (1980) as it is "the net summation of the moments at all three joints (i.e. ankle, knee and hip)". It represents a "limb pattern" which functions to push the whole body against the ground during stance phase of walking or running. While the trial-to-trial variation of individual joint moments is large, support moment has much reduced variability which is not affected by the trade-off among the extensor moments of the three joints (Winter, 2009). Winter further pointed out a similar profiles between support moment and vertical ground reaction force (GRF) (Winter, 2009). In addition, the analysis of contribution of each joint to the support moment provides an examination of the kinetic coordination strategy among the three joints in the lower extremity (Zeni and Higginson, 2011; Willy et al., 2017). Understanding the support moment and joint contributions during running at different slopes is important to determine the effects of sloped running on the kinetic synergy of the entire lower extremity and kinetic coordination strategy among the joints in the lower extremity.

Therefore, this study aimed to examine the 1) total support moment, a variable that incorporates hip, knee and ankle joint moments, and the 2) joint contributions of ankle, knee and hip to the total support moment during level, upslope and downslope running. The hypotheses of this study were 1) the total support moment would be different between the downslope, upslope, and level running conditions, and 2) the joint contributions of ankle, knee and hip will be different among the three running conditions.

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Specifically, we speculated that runners will exhibit largest support moment during upslope running, followed by level running and downslope running. Additionally, the contribution of the ankle, knee, and hip joints will be largest in upslope, downslope, and upslope conditions, respectively. The data obtained from this work may inform clinical decision making for training lower extremity musculature and/or preventing joint injuries in runners.

Methods

Participants

Twenty recreational runners (10 males and 10 females) between the ages of 21 and 40 years were recruited in this study. The data from an existing study were used to estimate the sample size for detecting changes in joint moments between level and sloped conditions (Park et al., 2019). With 95% power, and an α level of 0.05 and effect size of 0.95, the analysis estimated that 17 individuals would be needed to detect a significant change in knee moments between level and sloped running conditions. Participants were considered recreational runners if they ran at least six miles (approximately 9.7 km) per week for the last six months (Ho et al., 2019). Participants were excluded from the study if they had a lower extremity injury or surgery in the past six months and if they were pregnant, or thought they were pregnant. The average age, height, weight, and running distance per week of this cohort were 24.9 (SD 2.4) years, 1.70 (SD 0.07) m, 67.0 (SD 9.7) kg, and 13.8 (SD 5.6) km, respectively. Prior to participation, all subjects were informed of the nature of the study and signed a consent form approved by the Institutional Review Board of University of Nevada, Las Vegas.

Instrumentation

A 12-camera motion analysis system (Vicon, Oxford Metrics Ltd., Oxford, UK) was used to capture kinematic data of lower extremity and trunk at 250 Hz. Ground reaction forces were collected at a rate of 2000 Hz using force plates instrumented in a dual-belt treadmill (Fully Instrumented Treadmill, Bertec Corp., Columbus, OH, USA).

Procedures

Participants were tested in one session under three different treadmill running conditions: level, upslope, and downslope at a standardized speed of 2.3 m/s. Each participant started with 0° inclination (level condition), followed by 6° upslope or 6° downslope. The order of the upslope and downslope conditions was randomized. We chose 6° of slope as it is a common gradient seen in outdoor running (Abe et al., 2011). In addition, a relatively lower speed (2.3 m/s) was chosen as participants did not wear a safety body harness to ensure that the reflective markers on the trunk can be identified properly. In addition, 2.3 m/s running speed is thought to be as a comfortable speed that most runners can achieve across the three sloped conditions (Watkins, 2017).

Prior to the testing session, one same investigator placed markers on the trunk and lower extremities for all participants. The detailed marker definition has been reported in our previous work (Ho et al., 2018). In brief, anatomical markers were placed on the following anatomical landmarks: the great toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, L5 - S1 joint space, greater trochanters, iliac crests, anterior superior iliac spines, acromioclavicular joints, and posterior superior iliac spines. Additional tracking markers were attached on participant's lateral thigh, lateral leg, and heel counters bilaterally, as well as the spinous process of T3. A standing calibration trial was first obtained to define the segmental coordinate systems and joint axes. After the calibration trial, all anatomical markers were removed except for those at the iliac crests and L5 - S1 junction. The tracking markers remained on the participant throughout the running trials.

Each running condition began with a warm-up period in which participants ran at a self-selected warm-up speed for five minutes. Immediately following the warm-up, participants were asked to run at a speed of 2.3 m/s for each running condition. During each of the running conditions (upslope, level, and downslope), participants ran for three minutes, and three continuous 20-second trials were collected during the middle 1-minute. Participants were given a 5-minute rest period between conditions to avoid fatigue.

Data analysis

Vicon Nexus software (Oxford Metric Ltd., Oxford, UK) was utilized to label and digitize the reflective markers used to gather the kinematic data. Based on inverse dynamics method, the moments of the hip, knee, and ankle were computed using Visual 3D software (C-Motion, Rockville, MD, USA). Total support moment was calculated as the sum of the hip, knee and ankle joint moments in the sagittal plane during the stance phase of the running cycle (Winter, 1980). Each joint's contribution to the support moment was analyzed at the peak support moment and presented as a percentage of the total support moment (Zeni and Higginson, 2011). The middle five strides of each 20-second trial were analyzed for all participants. Thus, a total of 15 strides were analyzed for each participant.

Statistical analysis

The variables of interest included peak total support moment and hip, knee, and ankle joints' contributions to the support moment at the time of peak total support moment. All variables were examined on the right leg. A one-way ANOVA with repeated measures and post-hoc pairwise comparisons were used to compare the variables among the three running conditions. If a statistical significance was observed between the running conditions, post hoc t-tests were performed using a Bonferroni correction. Effect size of each comparison was calculated using Cohen's d. All statistical analyses were performed with the use of SPSS 24.0 statistical software (International Business Machines Corp, Armonk, New York). A significant difference was defined as p smaller than 0.05.

Results

One-way ANOVA with repeated measures showed that peak total support moment was significantly different among the three running conditions ($p < 0.001$). The post-hoc analyses showed that peak total support moment was significantly larger in upslope running when compared to level ($p = 0.009$; Cohen's d = 0.47) and downslope running ($p < 0.001$; Cohen's d = 0.92). Also, the peak total support moment during level running was significantly larger than downslope running ($p < 0.05$; Cohen's d = 0.52) (Figure 1).

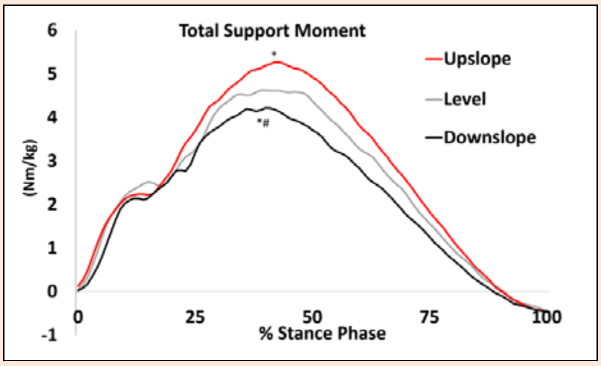

Figure 1. Total support moments of the three running conditions during the 100% stance phase of the running cycle. * indicates a significant difference from level; # indicates a significant difference from upslope (p<0.05).

One-way ANOVA with repeated measures showed that the joint contribution to total support moment was significantly different among the three running conditions for the hip ($p < 0.001$), knee ($p < 0.001$), and ankle ($p < 0.001$) joints. During upslope running, the participants demonstrated no significant difference in ankle, knee, or hip joint contribution to total support moment compared to level running ($p > 0.05$) (Figure 2). During downslope running, the participants demonstrated significantly larger knee contribution ($p < 0.001$; Cohen's d (downslope vs level) = 1.76; Cohen's d (downslope vs upslope) = 1.94), and significantly less ankle ($p < 0.001$; Cohen's d (downslope vs level) = 0.68; Cohen's d (downslope vs upslope) = 0.83) and hip ($p \leq 0.01$; Cohen's d (downslope vs level) = 0.56; Cohen's d (downslope vs upslope) = 0.87) contributions to the total support moment compared to level and upslope running (Figure 2). The individual joint moments during three different sloped conditions are also presented in absolute joint moment values (Figure 3).

Discussion

To the authors' knowledge, this is the first study comparing the total support moment, and the individual joint contributions of ankle, knee, and hip to the total support moment among upslope, level and downslope running. In support of our hypotheses, our results showed that peak total support moment was highest during upslope running and was lowest during downslope running. In addition, downslope running required highest knee joint contribution but least ankle and hip joint contributions when compared to level and upslope running.

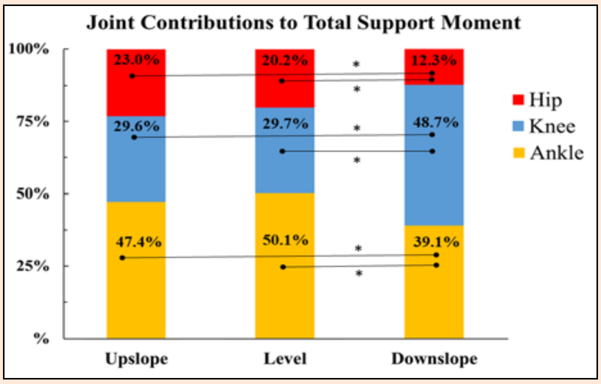

Figure 2. Hip, knee and ankle joint contributions of the three running conditions. * indicate p<0.05.

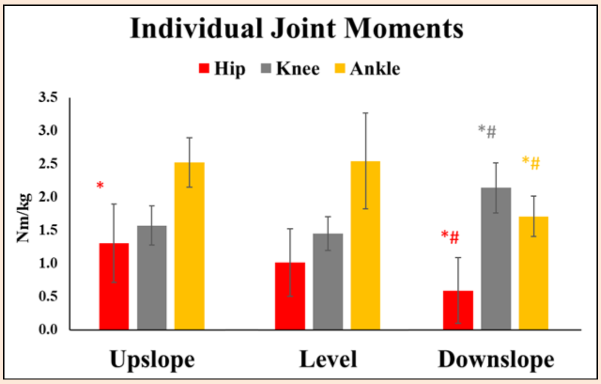

Figure 3. Individual joint moments (presented in absolute joint moment value) during the three running conditions. * indicate significant different from level; # indicate significant different from upslope using one-way ANOVA with repeated measures and post-hoc pairwise comparisons, $p < 0.05$.

Despite the fact that the recreational runners in our work experienced the largest peak total support moment during upslope running, joint contributions of the ankle, knee and hip were similar between upslope and level running. This suggests that the increased peak total support moment during upslope running was contributed by the three joints evenly. During downslope running, the knee joint contribution was larger than level and upslope running (19.0 % more than level and 19.1 % more than upslope) while the ankle and hip joint contributions were smaller than level and upslope running (ankle: 11% less than level and 8.3 % less than upslope; hip: 7.9 % less than level and 10.7 % less than upslope). In agreement with the existing literature, the support moment trajectory of our study shows a similarity to the vertical GRF trajectory during running (Figure 1) (Divert et al., 2005; Lieberman et al., 2010; Shih et al., 2013), suggesting that support moment is indicative of the mechanical demands of the lower extremity chain to overcome the vertical GRF.

Interestingly, while running in the three slope conditions (upslope, level and downslope) demonstrated similar amplitude of peak vertical GRF (Gottschall and Kram, 2005; Telhan et al., 2010; Ho et al., 2018), our results indicated runners experienced the largest peak total support moment on upslope followed by level and downslope. This suggest that, rather than GRF, the total support moment is more representative of the mechanical demands of the lower extremity joints. Such findings correspond to the findings of DeVita et al. (2008) who found that the total lower extremity joint work generated to uplift the body center of mass during upslope running was larger than the total lower extremity joint work generated to attenuate the impact shock during the same degree of downslope running. In addition, the setting of the downslope running in current study (-6°) has been shown as the "optimal slope" for running because of the minimal energy cost required at this steepness compares to level or other downslope steepness (Margaria, 1968; Dewolf and Willems, 2019). This idea is, in part, evidenced by the fact that the peak support moment at this optimal slope is less than that of level and upslope running observed in our work. Taken together, our data suggested that running upslope is deemed more strenuous while running downslope may minimize the mechanical demands of the lower extremity as compared to level running.

While the peak total support moment during downslope running was reduced compared to level running in our work, the joint contribution indicated a shift from an ankle dominant to a knee dominant running pattern (Figure 2). The increased knee moment contribution during downslope running compared to level running corresponds to the individual moment data reported in previous studies (Ho et al., 2018; Park et al., 2019). Such increases in knee extensor moment and knee joint contribution to total support moment were thought to be mainly driven by reduced trunk flexion during downslope running (Teng and Powers, 2014; Ho et al., 2018). Reduced trunk flexion during running is thought to cause posterior shift of body center of mass, increasing external moment arm of the knee and knee extensor moment (DeVita et al., 2008). It is suggested that increased eccentric contraction of the knee extensors during downslope running may enhance the activation of muscle spindle (Gregor et al., 2006) and could contribute to the increased knee extensor activity (Lay et al., 2007) and therefore result in a knee dominant pattern.

The data of joint contributions to support moment can provide important insights into rehabilitation and training of runners. For example, the knee dominant pattern during downslope running observed in our work may have an effect on muscle tissue, muscle strength, and knee joint loading. From muscle strengthening perspective, the highest knee extensor demand required during downslope running can facilitate the improvement of knee extensor strength of runners when training downslope running. This concept agrees with Toyomura et al. (2018) that runners gained knee extensor strength after 5 weeks of downslope running training and the same effect was absent after 5 weeks of level running. From joint loading perspective, increased knee extensor moment contribution during downslope running results in higher patellofemoral joint stress, which can cause more patellofemoral symptoms in runners with patellofemoral pain (Ho et al., 2018). At the tissue level, Maeo et al. (2017) utilized T_2 value from magnetic resonance imaging as an index of the inflammatory edema of muscles and found a single bout of 45 min of downslope running induces knee extensor muscle damage, likely due to repetitive, higher levels of quadriceps eccentric contraction (i.e., increased quadriceps force demand over higher excursion of knee flexion) in downslope running. As such, it is believed that training slopes should be taken into consideration by the coaches/healthcare providers, depending upon the goals of the training and/or the purposes of minimizing specific injuries to the runners.

This work provides a systematic understanding of the effects of sloped running on the lower extremity kinetic profiles, however, several limitations of this study should be considered when interpreting the results. The participants we recruited represent asymptomatic young runners with regular running routines. The results may not be applicable to other age populations or runners with musculoskeletal conditions. Second, the participants ran only eight minutes in total (five minutes warm up plus three minutes data acquisition) on each slope condition. Therefore, the results of this study may not reflect the status of a long-distance run or running under fatigue. Third, only one controlled speed and one degree of slope were tested in our work. Future studies are needed to understand the support moments and joint contributions under different degrees of sloped running surfaces with different running speeds. Fourth, the total support moments were calculated based on the net joint moments from inverse dynamics in the sagittal plane. The net joint moments only reflected the net sum of the extensor and flexor moments of each joint and did not reflect the absolute joint loading when both extensor and flexor moments were in substantial amplitudes. Future studies using methodology such as simulated musculoskeletal modelling are needed to understand the differences of the absolute joint loading among the three sloped conditions.

Conclusion

This study shows that different lower extremity loading profiles were used in runners when running on different sloped surfaces. Specifically, while downslope running requires the least total support moment, highest knee joint contribution and least ankle and hip joint contributions were observed when compared to level and upslope running. Clinicians and coaches may consider the training slopes for runners based on the training purposes and/or individual musculoskeletal conditions of the runners to prevent running injuries.

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Key points

- Runners experience different task demands from biomechanical, physiological and neuromuscular aspects among upslope, downslope, and level running.
- Inconsistent findings comparing individual lower extremity joint moments among different sloped conditions were reported previously.
- Support moment provides a comprehensive insight into the kinetic synergy of the overall limb; however, the influences of upslope, level and downslope running on the support moment were not thoroughly examined.
- Our results demonstrated that upslope running increased the summed moment of the lower extremity joints, while the increased summed moment was evenly distributed among the three joints.
- We also found that running downslope decreased the summed moments of the lower extremity joints in total as well as the hip and ankle joint contributions. However, the knee joint contribution during downslope running increased compared to level and upslope running.

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