KNEE JOINT BIOMECHANICS UNDER SYSTEMATICALLY INCREASED LOADING CONDITIONS IN RUNNING

Katina Mira Fischer[1], Steffen Willwacher[1], Martin Küsel-Feldker[1] and Gert-Peter Brüggemann[1]

Institute for Biomechanics and Orthopaedics, German Sport University, Cologne, Germany[1]

The purpose of this study was to identify the general and individual biomechanical response to increased vertical loading with a particular emphasis on the knee joint in running. Biomechanical analysis was performed in three different loading conditions (100%, 110%, 120% body weight) by means of a standard inverse dynamics procedure using a Vicon Nexus system and an instrumented treadmill. Increased vertical loading was accompanied by increased peak internal knee abduction moments and a small increase (0.6°) of knee adduction angles. Two adaptation mechanisms could be identified, differing with respect to the increase of peak vertical GRF and abduction moments. It might be that runners aim at maintaining their habitual joint motion path, choosing a strategy that corresponds to their capacities to resist additional external loads.

KEY WORDS: running biomechanics, vertical load, knee joint.

INTRODUCTION: The knee joint is the most common side of overuse injuries in distance running (Ferber, Hreljac & Kendall, 2009). Each joint in the skeleton is considered to follow a path of least resistance, which is dominantly determined by the shape of articular surfaces, tendon, ligaments and muscles surrounding the joint (Nigg, Nurse & Stefanyshyn, 1999). This path of least resistance can be described as the habitual joint movement path (HJMP) and is related to a minimum of intra-articular mechanical loading. Increased external vertical loading might represent a challenging situation for maintaining the HJMP. Higher joint moments might be required to sustain similar joint kinematics under increased loading. Runners might be differing in their capacities to keep the HJMP (i.e. creating increased internal joint moments), which might be reflected in individual response strategies to increased vertical load. Only limited findings exist regarding the biomechanical response of the knee joint to altered vertical load (Cross, Brughelli & Cronin, 2014; Chang, Huang, Hamerski & Kram, 1999). An improved understanding might provide greater insight into joint load regulation of runners using added weights like backpacks. Further, it will provide greater insight into the robustness of the HJMP to external perturbations. The frontal plane of motion is of particular interest, as knee joint loading in this plane has been linked to overuse injuries like patellofemoral pain syndrome and to the progression of tibio-femoral osteoarthritis (Andriacchi, 1994; Stefanyshyn, Stergiou, Lun, Meeuwisse & Worobets, 2006). Therefore, the purpose of this study was to identify the general and individual biomechanical response to increased vertical loading with a particular emphasis on the knee joint in running.

METHODS: For this purpose, a device to systematically increase vertical loading while running on an instrumented treadmill was developed. The device is able to apply a nearly constant downward directed force to a subject near the center of mass by use of a modified wetsuit (Figure 1). Ropes attached to four pneumatic cylinders (type: DSNU, Ø 25mm Festo, Esslingen, Germany) mounted to the edges of an aluminum frame above the subjects head, were thread through four deflecting rolls attached to the frame of the treadmill and fixed to the wetsuit using carbines. Two precision regulating valves (LRP-1/4-10, Festo) were used to ensure constant pressure of the pneumatic cylinders.

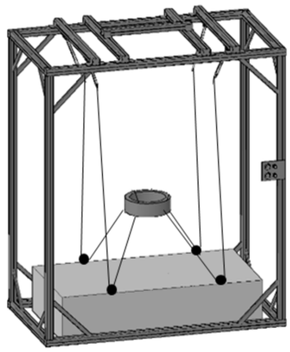

Figure 1: Schematic figure of the device to systematically increase loading, where a ring replaces the custom - made harness and the instrumented treadmill is replaced by a box.

Fifteen male subjects (26.1 ± 2.6 years; 179.6 ± 4.3 cm; 77.4 ± 7.6 kg) were analysed while running in a neutral racing flat (Brooks, Racer T7) on an instrumented force treadmill (Treadmetrix, Park City, UT, USA, 1000 Hz). The treadmill consisted of an aluminum belt unit which was carried by four load cells (AMTI, Watertown, MA, USA). The load cells were mounted on four heavy steel columns, connected to a 350 kg base steel plate. Force data were filtered using a fourth order, recursive Butterworth filter with a cutoff frequency of 40 Hz. Joint kinematics and kinetics were calculated using a five segment inverse dynamics model of the right lower extremity, following the equations of Hof (1992). Kinematic data were obtained using a ten camera opto-electric system (Vicon Nexus Systems, Oxford, UK 250 Hz). The experimental protocol consisted of three different load conditions: 100%, 110% and 120% body weight. Per condition, 20 step cycles were included into data analysis. The running speed was set to 3.0 m/s. Statistical comparisons were made using repeated measures ANOVA. Further, pairwise comparisons were performed using paired samples t-tests with Bonferroni corrections ($\alpha = 0.05$).

RESULTS: With increased vertical load the vertical impulse (VI) increased systematically. Increased peak vertical GRF (pvGRF) were observed for the 120% body weight (BW) condition with respect to both other conditions. Contact times (CT) were significantly prolonged during running with additional loading. Higher internal knee abduction moment (iAbdM) amplitudes were found in 120% BW condition compared to both other conditions. A small but significant difference of 0.6° of the maximum knee angle in the frontal plane (KAfr) was detected between 120% and 100% BW. Comparing the 120% BW to the 100% BW condition, effects sizes (Cohen's d) were higher for the increase of iAbdM (d = 1.01) compared to the increase of KAfr (d = 0.75). Table 1 summarizes the statistical results.

Table 1
Statistical results, given as mean ± standard deviation.

		100% BW	**110% BW**	**120% BW**
Contact time [ms]	L	0.25 ± 0.02 ^{b,c}	0.26 ± 0.02 ^{a}	0.27 ± 0.02 ^{a}
Peak vertical GRF [N/kg]	L	24.84 ± 2.03 ^{c}	24.72 ± 1.92 ^{c}	25.78 ± 2.09 ^{a,b}
Vertical impuls [N*s]	L	3.61 ± 0.18 ^{b,c}	3.74 ± 0.17 ^{a,c}	3.98 ± 0.18 ^{a,b}
Min. knee int. abduction moment [Nm/kg]	L	-1.07 ± 0.30 ^{c}	-1.11 ± 0.31 ^{c}	-1.19 ± 0.33 ^{a,b}
Max. knee angle frontal plane [deg.]	L	5.27 ± 2.81 ^{c}	5.74 ± 3.24	5.87 ± 3.37 ^{a}

L: significant load effect (p<0.05)

a, b,c: Significant (p<0.05) difference to 100%, 110% or 120% load condition, respectively.

Looking at individual data, runners showed different response patterns to increased vertical loading. In the 120% BW condition, eight subjects increased pvGRF distinctly (group 1) compared to the baseline, while seven subjects kept their pvGRF almost constant (group 2) (Figure 2). Subjects were assigned to the groups based on a threshold of 2.52% after visual inspection of the pvGRF change distribution. All subjects of group 1 increased their iAbdM, whereas group 2 displayed on average a tendency to keep their iAbdM on a similar level (Figure 1).

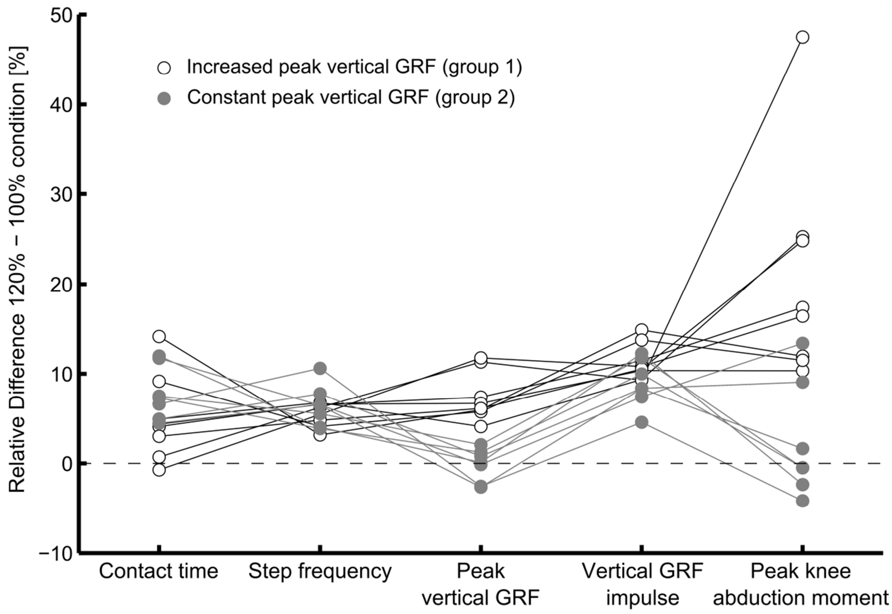

Figure 2: Individual response strategies in contact time, step frequency, peak vertical GRF, vertical GRF impulse and peak knee abduction moment. Runners were divided into two groups based on their change in average peak vertical GRF.

Looking at mean values of absolute KAfr, no systematic differences between groups could be found (Figure 3), even though it appears that the initial increase in KAfr from 100% to 110% BW is more pronounced in group 1.

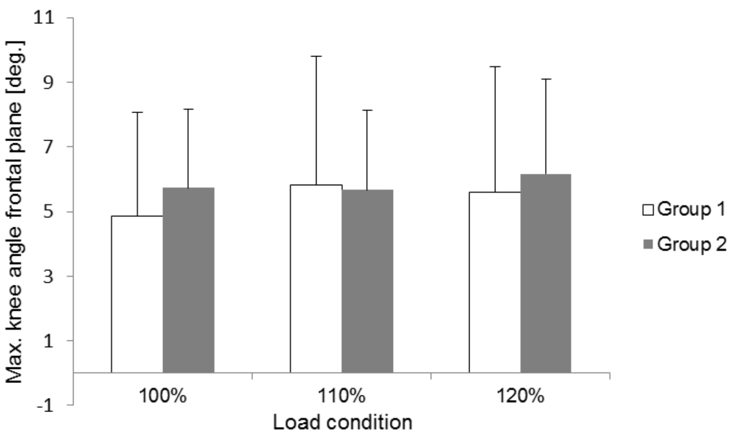

Figure 3: Mean maximum knee angles in the frontal plane (mean + stem) of subjects that increased pvGRF and those who decreased pvGRF for the different loading conditions.

DISCUSSION: The results of the study show that running in increased vertical loading conditions is related to increased iAbdM and KAfr. The fact that effect sizes were higher for changes of iAbdM compared to KAfr might indicate that runners try to maintain their HJMP by internal moments resisting the higher external load. Additionally, observed differences in KAfr averaged only 0.6°. Nonetheless, an increase of the internal knee abduction impulse is deemed a risk factor in the genesis of patellofemoral pain syndrome (Stefanyshyn, Stergiou, Lun, Meeuwisse & Worobets, 2006) and is considered to contribute to the progression of degenerative processes at the knee (Andriacchi, 1994).
For running under increased vertical loading a higher vertical impulse per running distance is required to ensure an oscillating centre of mass motion. Subjects of group 1 increased the VI by increasing pvGRF, while only moderately raising CT and step frequency. Group 2 avoided an increase of pvGRF by increasing CT and step frequency more pronounced than group 1. Since increased pvGRF are leading to higher iAbdM, the response in stride characteristics of group 2 can be considered as strategy to avoid amplified iAbdM. It might be assumed that subjects with poor muscular capacities would try to avoid an increase of pvGRF and therefore higher iAbdM, in order to be able to maintain the habitual joint motion path. On the other hand, runners with stronger muscular abilities might be capable of realising and tolerating an increase in iAbdM.

CONCLUSION: The results of the study give evidence for some of the assumptions of the HJMP theory. Further it was shown that different response strategies to increased loading exist, which might be related to the individual capacity to counteract increased external load.

REFERENCES:

Andriacchi, T. P. (1994). Dynamics of knee malalignment. *Orthopedic Clinic of North America,* 25(3), 395-403.

Chang, Y. C, Huang, H. W. C., Hamerski, C. M., Kram, R. (2000). The Independent Effects of Gravity and Inertia on Running Mechanics. *The Journal of Experimental Biology,* 203, 229-238.

Cross, M. R., Brughelli, M. E., & Cronin, J. B. (2014). Effects of Vest Loading on Sprint Kinetics and Kinematics. *Journal of Strength and Conditioning Research,* 28(7), 1867-1874.

Ferber, R., Hreljac, A., & Kendall, K. D. (2009). Suspected Mechanisms in the Cause of Overuse Running Injuries: A Clinical Review. *Sports Health: A Multidisciplinary Approach,* 1(3), 242.

Hof, A. L. (1992). An explicit expression for the moment in multibody systems. *Journal of Biomechanics*, 25(10), 1209-1211.

Nigg, B. M., Nurse, M. A., & Stefanyshyn, D. J. (1999). Shoe inserts and orthotics for sport and physical activities. *Medicine and Science in Sports and Exercise,* 31(7 Suppl), S421-428.

Stefanyshyn, D. J., Stergiou, P., Lun, V. M., Meeuwisse, W. H., & Worobets, J. T. (2006). Knee angular impulse as a predictor of patellofemoral pain in runners. *American Journal of Sports Medicine,* 34(11), 1844-1851.