FRONTAL PLANE LOWER LIMB KINEMATICS CHANGE AT TOE-OFF FOR LOADED WALKING TO MAINTAIN MEDIAL-LATERAL GAIT STABILITY

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The purpose of the study was to examine the impact of carrying backpack loads on the medial-lateral gait parameters. Seventeen primary school boys walked on an instrumented treadmill with 10%, 15% and 20% bodyweight loads. At the instance of toe-off of the ipsilateral leg, the whole body weight is supported by the contralateral leg. The shift to single leg support may render the gait unstable. However, a three-dimensional kinematic analysis revealed that at toe-off, the body adopts certain frontal plane gait changes at the knee to control the moment induced in the frontal plane by the quasi-force couple of the gravitational force on the centre of mass (COM) and the vertical normal reaction force on the contralateral supporting leg. For the loaded conditions, since the magnitude of the gravitational force and the normal reaction force increases because of the additional backpack load, the increase in the magnitude of the quasi-force couple is regulated by a change in knee kinematics.

KEY WORDS: frontal, gait, stability, backpacks, loaded

INTRODUCTION:

The task of maintaining balance in the medial-lateral direction is complex and is very difficult because the narrow width of the base of support (BOS) during the single support phase of the gait cycle (MacKinnon and Winter, 1993). Balance of the head, arms and trunk (HAT) about the supporting hip and the centre of mass (COM) about the supporting foot are two primary mechanisms of balance control in the medial-lateral direction. Previous studies have also indicated that total body balance is achieved by the regulation of the angular motion of the total body COM about the supporting foot and foot placement at heel-strike (MacKinnon and Winter, 1993). At the point of toe-off, the whole body-weight is supported by only one leg. This instantaneous shift to one leg support may induce gait instability and may put young children at the risk of tripping over when they are carrying heavy backpack loads. The purpose of the present study was to investigate how load carriage on the back affects the gait kinematics in frontal plane at the point of toe-off and the mechanisms the body employs to maintain stability in the frontal plane.

METHOD:

All experimental procedures were conducted indoors, at the Sports Biomechanics Laboratory, Physical Education and Sports Science (PESS), Nanyang Technological University, Singapore. Ethical approvals for the experimental and theoretical aspects of the study were sought from and approved by the Research and Graduate Review Committee of the PESS group. Seventeen primary school boys with mean age of 9.65 (±1.58) years, mean height 134.41 (±11.01) cm and weight 31.09 (±7.01) kg participated in the study. The walking protocol involved walking at self-selected speeds under different load conditions on an instrumented Gaitway™ treadmill for six minutes. Kinematic data was collected for ten seconds at the end of the six minutes. One gait cycle was chosen at random from the ten seconds of collected data to do the kinematic analysis. Subjects walked with three different backpack loads that were 10, 15 and 20% of their bodyweights (BW). Subjects also walked without load for a baseline measurement. Kinematic data was collected using a synchronized six-camera optical motion analysis system by Motion Analysis Corporation (MAC). Data was collected at 60 Hz at a shutter speed of 0.001 seconds. The collected data was interpolated with the cubic spline technique and smoothed with a Butterworth low pass band filter at 6 Hz. A modified Helen-Hayes marker configuration was used. The treadmill and motion analysis system were synchronized using an external trigger. Symmetry between legs was assumed and the right leg was chosen as the ipsilateral leg. The pelvic, hip, knee and ankle frontal plane motion were recorded over one gait cycle. Gait cycle was defined from the right foot heel-strike to the next right foot heel-strike. The foot progression angle in global co-ordinates over one gait cycle was also recorded. P was set at 0.05. Repeated measures ANOVA analyses (with Bonferroni confidence interval adjustment) were used. Tukey's Post-Hoc test was used whenever significant differences were found.

RESULTS AND DISCUSSION:

No significant differences were found between the loaded and unloaded condition for the foot progression angle at heel-strike, mid-stance and toe-off. However, throughout the stance phase and after toe-off, with respect to the direction of progression, the foot was more medially oriented for the loaded conditions as compared to the unloaded condition (Figure 1 and Table 1). During the unloading phase of the gait cycle and after toe-off till about 80% of the gait cycle, the loaded conditions show higher medial foot progression angle than the unloaded condition.

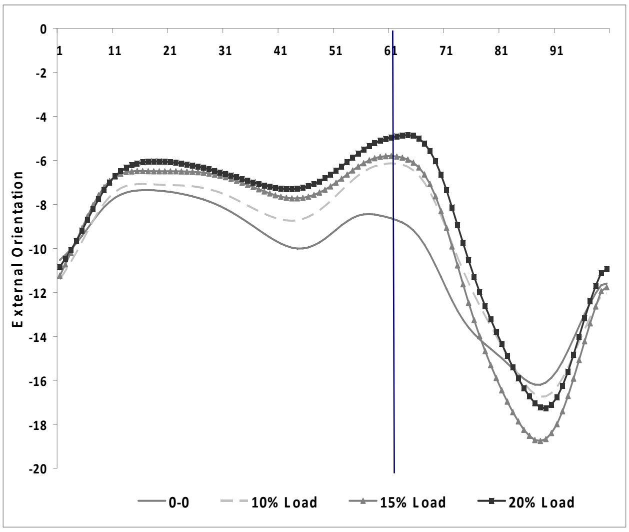

Figure 1: Mean foot progression angle over the gait cycle for the four conditions. The vertical line denotes toe-off.

No significant differences were observed between the loaded conditions and unloaded condition for the ankle inversion-eversion at heel-strike, mid-stance and toe-off for the ipsilateral leg (Figure 2 and Table 1). However, for the loaded conditions the ankle was more inverted from heel-strike to mid-stance (though these differences were not significant). For the 15 and 20% load conditions, the ankle was more inverted and more medially oriented in the transverse plane through out the stance phase (Figure 1 and 2). For the knee varus-valgus angles, no significant differences were observed at heel-strike or mid-stance (Figure 2). Significant differences were found at toe-off ($p < 0.05$). Knee varus angle from slightly before mid-stance and during the unloading phase to toe-off was higher for the loaded conditions as compared to the unloaded condition. Higher loads led to higher varus angle at the knee (Table 1). The hip abduction-adduction angles showed no significant differences over the gait cycle. However, the hip was less abducted during the unloading phase, at toe-off and after toe-off for the loaded conditions as compared to the unloaded condition (Figure 2 and Table 1). In contrast to the findings of Smith et al. (2006), no differences were found for the frontal plane pelvic movement. Therefore, besides the knee varus angle at toe-off, the other lower limb joint and pelvis angles were similar over the gait cycle between the loaded and the unloaded condition.

Table 1: Descriptive statistics for frontal plane angles at toe-off of ipsilateral leg and the foot progression angle

Load Condition	Foot Progression Angle	Ipsilateral Ankle	Ipsilateral Knee	Ipsilateral Hip
No Load	-8.63 (±6.68)	2.09 (±2.69)	5.68* (±9.55)	-9.69 (±4.95)
Load 10%	-6.19 (±6.75)	1.75 (±2.53)	9.44 (±11.02)	-8.86 (±4.40)
Load 15%	-5.82 (±6.52)	1.75 (±2.82)	9.83 (±12.02)	-8.89 (±4.84)
Load 20%	- 4.85 (±6.54)	1.09 (±2.38)	12.67* (±9.76)	-8.63 (±3.49)

*** P<0.05**

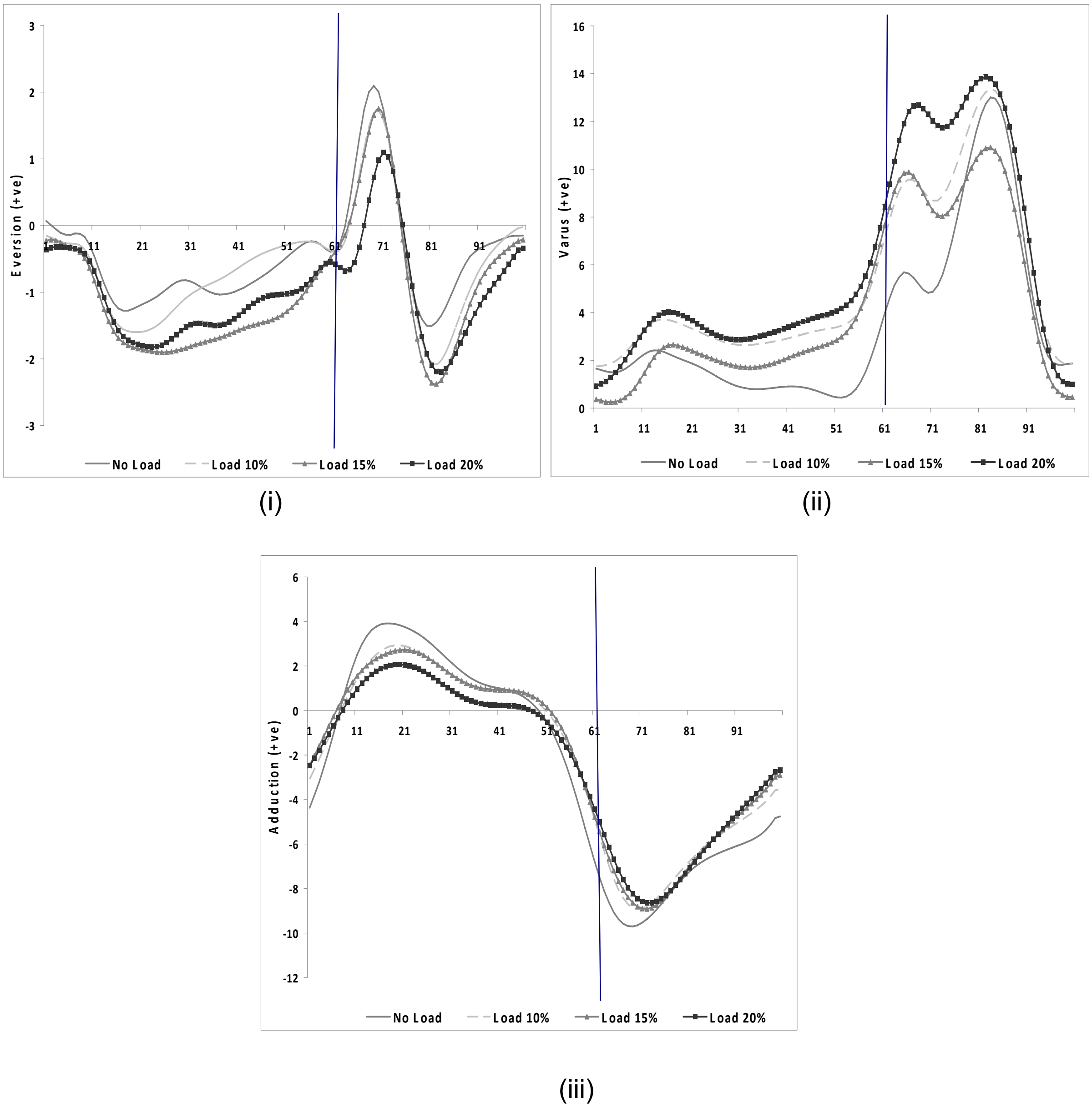

Figure 2: (i) Ankle inversion-eversion over one gait cycle; (ii) Knee varus-valgus angle over one gait cycle; and (iii) Hip abduction-adduction over one gait cycle. The vertical line denotes toe-off.

At the point of toe-off, the hip was less abducted for the loaded conditions compared to the unloaded condition (Figure 2 and Table 1). This could be because the hip abductors cause the hip to be less abducted for loaded conditions to maintain balance in the medial-lateral direction. This would bring the COM of the head, arms and trunk (HAT) and the backpack within the medial-lateral BOS. This control of the HAT and backpack about the supporting hip is achieved by the hip abductors and from passive assistance from medial acceleration of the hip joint which counters the large gravitational moment of the HAT (MacKinnon & Winter, 1993). Since the HAT is almost 2/3 of the overall mass of the body, this mechanism of controlling abduction may allow for the COM of the HAT and backpack load to be moved closer towards the centre of the contralateral leg BOS.

Immediately after the toe-off of the ipsilateral leg, the whole weight of the body and backpack load is supported by the contralateral leg. In other words, the centre of pressure passes solely through the contralateral leg BOS. After toe-off of the ipsilateral leg, the contralateral

foot is undergoing inversion, the contralateral knee is under varus and the contralateral hip is undergoing slight adduction and internal rotation (Figure 2). Due to the combined effect of all these, the COP moves more medially on the contralateral foot.
For the ipsilateral leg, the orientation of the knee and hip joint changes to align the line of gravity more medially towards the contralateral BOS. This reduces the moment arm of the gravitational force and the normal reaction force couple. Even though the gravitational and normal reaction forces are different in magnitude, but over a gait cycle they are close to one body-weight (BW) and can therefore be treated as a quasi-couple. We may term it as a quasi force-couple. In other words, the lower hip abduction, the higher varus angle at the ipsilateral knee, and the higher inversion and internal orientation of the foot at the contralateral ankle for the loaded conditions reduced the length of the moment arm for the rotational couple in the frontal plane. These changes possibly restrict the magnitude of the rotational coupling torque from increasing beyond reasonable limits and provide gait stability.

CONCLUSION:
The strategies employed at the hip, knee, and ankle supports the postulation of MacKinnon and Winter (1993), that the control over the lateral trajectory of the COM is achieved by regulating the angular rotation of the whole body COM about the BOS. The control is regulated by the distance between the frontal plane gravitational force vector and the frontal plane reaction moment force vector. The present study also indicated that the knee joint was also responsible for controlling the balance in the medial-lateral direction. This is stark contrast to the findings of MacKinnon and Winter (1993) who suggested that only the subtalar joint and the hip joint are responsible for synergizing the balance in the medial-lateral direction. The significantly higher knee varus angle at toe-off indicates that loaded walking may impose a significant strain on the knee abductors-adductors.

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Acknowledgement
The authors would like to acknowledge United BMEC Pte. Ltd, Singapore for their kind logistical support provided during the study.