

# **If It's Not a Slip, Trip, or Fall, What Is It? Biomechanics of Walking on Railroad Ballast**

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**Abstract.** Five healthy male subjects (mean age = 31.8 yr, mean height = 181.4 cm, mean weight = 83 kg) walked on level concrete, yard ballast (rock about 1.9 cm across), and mainline ballast (3.8 cm) while their rearfoot motion was measured. The ballast was placed in trays (4.9 m long, 0.9 m wide, 20 cm deep) that were tilted 7 degrees in the transverse plane. Rearfoot motion was measured by an Optotrak system while the subjects walked the length of the trays wearing work boots. Standard biomechanical techniques were used to acquire and process the rearfoot motion data. A repeated measures ANOVA and a subsequent multiple comparison test revealed that the rearfoot range of motion was significantly greater walking on the mainline ballast than walking on either the yard ballast or the concrete. In fact, the mean range of rearfoot motion for yard ballast was not significantly different from that resulting from walking on concrete. Variability was more than twice as great walking on mainline ballast than walking on level concrete. Rearfoot angular velocities walking on level concrete and yard ballast were not significantly different, but both were significantly less than walking on mainline ballast. These data confirm that railroads should place smaller (yard) ballast in locations where trainmen have to walk as part of their jobs.

## **1. INTRODUCTION**

Railroad workers required to walk on ballast experience slips, trips and falls, but they have also been developing lower extremity musculoskeletal disorders (MSDs). Trainmen work in railroad yards or on the road to make-up trains, inspect cars, and

drop off or pick up cars at industrial sites. A significant portion of their work day involves walking on ballast - the rock that is laid down to support the rails and provide drainage. Ballast rock comes in different sizes and railroads have established guidelines for ballast size specifying smaller ballast to be used in the yards where more walking takes place. This study was an investigation into the mechanisms of loading of the lower extremity that could lead to MSDs even when slips, trips, or falls don't occur. The testing quantified rearfoot motion of subjects walking under different conditions that represent typical walking tasks of railroad workers. Rearfoot motion has been used to test the differences between shoes (Greer et al., 1987), the effects of ankle supports (Hamill, Morin, Clarkson, and Andres, 1988), and other investigations of lower extremity function (Campbell et al., 1987; De Wit et al., 2000).

## 2. METHODS

Five healthy male subjects (mean age = 31.8 yr, mean height = 181.4 cm, mean weight = 83 kg) gave their informed consent to participate in the experiment. Subjects were paid thirty dollars per hour for their efforts.

Ballast was procured from a local quarry that supplies ballast for CSXT in Western Massachusetts. They supplied us with CSX 3-4, described as 1-1/4" to 1-1/2" (3.175 - 3.81 cm) *main line ballast*, and 3/4" (1.905 cm) *walking ballast*. Screen analysis confirmed that these products conformed to CSXT gradation requirements.

Two trays were constructed to contain the ballast for the walking tests. Each tray was 4.9 m long, 0.9 m wide, and 20 cm deep. Ballast was placed in each tray to a depth of at least 16 cm. The trays were located side-by-side with 61 cm of level concrete floor between them - this concrete surface was used for the level walking condition on firm footing. Each tray was tilted at 7 degrees in the transverse plane, confirmed by inclinometer. This meant that the subjects walked on ballast with the left foot above the right foot.

Each subject wore work boots for all of the trials. These work boots were purchased new at Wal-Mart. They were made by Brahma, had oil resistant soles, distinct heels, steel toes, and laced above 15.24 cm. These boots complied with railroad requirements for their employees working near tracks.

Video data were collected by cameras in both the frontal and sagittal planes to document the sessions. Infrared light emitting diodes (IREDS) were placed bilaterally on the back of each subject's lower legs. Four IREDS were placed on each leg - two on the posterior aspect of the bisected calf and two on the bisected heel of each boot. Three-dimensional kinematic data were collected at 100 Hz through an Optotrak 3020 System (Northern Digital Inc., 403 Albert Street, Waterloo, Ontario, Canada, N2L 3V2) which had its position sensor bank behind the subject. Kinematic data were collected for 5 seconds, during which the subjects completed the walk along the length of the walkway.

Stance phase was determined as the period where the velocity of the heel marker on each foot in the antero-posterior direction was less than 0.05 m/sec. Stance phase was studied because that is when the foot is in contact with the walking surface.

The raw kinematic data were converted into 3D data by means of the Optotrak system software. Missing data were interpolated using a linear difference algorithm. If there were more than 15 consecutive frames of missing data within any particular stride, that stride was discarded because the interpolation was not reliable. The interpolation procedure was validated against known values before its use and

demonstrated a maximum error of 1.0 mm. After interpolation, the data were filtered at 5 Hz (low pass second order Butterworth).

Before donning the boots and IRED markers, each subject had their feet clinically screened by a physical therapist. This assessment included a history of chronic lower extremity or low back injury, determination of flat feet or high arched feet, measurement of hyperpronation, determination of late pronation, forefoot varus and rearfoot varus, and callus patterns. All subjects tested in the normative range for each of these parameters.

After lacing on the boots, the IREDs were positioned on the back of each leg and boot as described above. Subjects then stood stationary at the proximal end of the walkway designated for their first testing condition while calibration of the optoelectronic data capture system took place. Subjects then walked the length of the particular walkway several times to practice and to assure that the data collection was working properly. Subjects then completed 15 trials of walking on each walking surface while optoelectronic data were acquired. After completing a given condition the subject moved to the next scheduled walkway surface and the calibration, practice, and data acquisition procedures were repeated. Each subject performed 15 trials of walking on each of the three surfaces. After each condition they were asked about the perceived exertion of the previous walking condition (Borg's 10 point rating scale used).

Subjects walked at their freely chosen comfortable pace. The ballast in the trays was redistributed by rake after each subject so that the surface did not develop any ruts or concavities.

### **3. RESULTS**

After the data were smoothed by filtering, the stance phase of each foot was determined. For some trials more than one stride was successfully collected for each foot. The resulting total number of stance phases evaluated was 700.

Five parameters were derived from the processed kinematic data: range of motion of the rearfoot angle, rearfoot angle at heel strike, the variability of the rearfoot angle range during the stance phase, angular velocity of rearfoot motion, and the angular acceleration of the rearfoot. Another parameter (rating of perceived exertion) was obtained from questionnaire responses.

The analysis involved 5 subjects, 3 conditions (flat, *walking*, and *main line ballast*), and 2 sides (right and left). Repeated measures analysis of variance techniques were applied using a generalized linear model to account for the different number of data points per cell.

Rearfoot motion range was calculated as the angular excursion from maximum inversion to maximum eversion. The range of rearfoot motion was significantly different between subjects and due to walking conditions within subjects. However, there was not a significant difference between the left foot (the uphill leg) and the right foot (the downhill leg), so these data were combined for further analysis. Once combined, a Duncan's multiple range test was performed to test whether means were significantly different. This analysis revealed that the rearfoot range of motion was significantly greater walking on the *main line ballast* than walking on either the *walking ballast* or the concrete (see Table 1). In fact, the mean range of rearfoot motion for *walking ballast* was not significantly different from that resulting from walking on concrete.

The rearfoot touchdown angle represents the amount of inversion/eversion experienced at the beginning of the load acceptance phase of stance. Recall that the walking conditions tested included level concrete and tilted ballast surfaces,

hence it was not expected that a direct comparison between level and tilted surfaces would be meaningful. Statistical analysis revealed that there were significant differences in rearfoot angle at heel-strike due to the walking condition. The Duncan's multiple range test found that the mean angle was -0.698 degrees for the level concrete condition, -6.155 degrees on the walking ballast, and -6.323 degrees for the main line ballast. There was a significant difference in rearfoot angle at heel-strike between walking on the level concrete and walking on the tilted ballast. However, there was no significant difference between the values found on the different sizes of ballast.

Table 1: Mean values (and standard deviations in parentheses) of the criterion measures.

Dependent Variable	Walking Condition		
	Level Concrete	Walking Ballast	Main Line Ballast
Range of Rearfoot Motion (degrees)	3.08 (1.17)	3.48 (1.68)	5.50 (2.84)
Variability in Rearfoot Range of Motion (degrees)	1.11 (0.25)	1.63 (0.40)	2.70 (0.71)
Angular Velocity of Rearfoot (deg/s)	33.92 (18.93)	37.42 (19.2)	45.09 (23.32)
Angular Acceleration of Rearfoot (deg/s/s)	1052.69 (660.5)	1115.17 (618.6)	1222.46 (766.8)
Ratings of Perceived Exertion (Borg 10 point scale)	0.4 (0.22)	1.3 (0.67)	3.4 (1.14)

The variability in the rearfoot angle range is of interest because it represents additional challenge faced by the neuromusculoskeletal system in terms of passive tissue loading and active neuromuscular control. There was a significant effect of walking condition on the variability in the range of rearfoot motion. The variability increased as the subjects walked on level concrete, *walking ballast*, and *main line ballast*, respectively (Table 1). Variability was more than twice as great walking on *main line ballast* than walking on level concrete. Rearfoot motion was not as variable on *walking ballast* as on *main line ballast*, but it was more variable than on level concrete.

The angular velocity of the rearfoot during the stance phase was derived from the positional data. The repeated measures analysis revealed that subject, walking condition, and side (left v. right) all had a significant effect on angular velocity. If the data from both sides were grouped, a Duncan's multiple range test revealed that angular velocities walking on level concrete and *walking ballast* were not significantly different, but both were significantly different from walking on *main line ballast* (see Table 1).

Angular acceleration of the rearfoot was calculated because it relates to the forces exerted by the supporting tissues (e.g. ligaments and joint capsules) in the feet and legs. The angular acceleration of the rearfoot during the stance phase was derived from the angular velocity data. The repeated measures analysis revealed that subject and walking condition both had a significant effect on angular

acceleration (Table 1). The angular acceleration increased as the subjects walked on level concrete, *walking ballast*, and *main line ballast*, respectively.

Borg's 10 point scale to rate perceived exertion was completed by each subject when they finished each walking condition. The results are summarized in Table 1. The RPEs increased as the subjects walked on level concrete, *walking ballast*, and *main line ballast*, respectively.

#### 4. DISCUSSION

The overall finding from this study is that walking on *main line ballast* significantly increases the biomechanical loading of the lower extremities compared to walking on *walking ballast*. These increased biomechanical loads are reflected in the increased rearfoot range of motion, the increased variability in rearfoot motion, the increased angular velocity, and the increased angular acceleration of the rearfoot when walking on *main line ballast*. These increased stresses, over the course of a railroad career, can lead to chronic and acute disorders in the lower extremities.

These stresses can be minimized by using *walking ballast* in those locations where railroad employees must walk and work. In fact, *walking ballast* can decrease the biomechanical stresses to those experienced when walking on level concrete. The concomitant decrease in foot rolling motions also decreases the risk of slips, trips, and falls - a major concern for railroad safety efforts.

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