THE EFFECTS OF LOAD AND SPEED ON THE GROUND REACTION FORCES OF THE SOLDIER DURING UPHILL, DOWNHILL AND LEVEL WAKING

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The objective of this study was to determine the effects of load, speed and gradient on ground reaction forces of soldiers. Decline walking resulted in significant increases in peak loading rates, impact peak loads, braking forces and decreases in propulsive forces when compared to level and incline walking. The peak loading rates, vertical impact peak and anterio-posterior braking forces were significantly lower during the loaded condition compared to the unloaded condition during downhill walking. In addition, the first half of the stance phase was found to be significantly longer when carrying a load during level and decline walking suggesting individuals adopted compensation strategies to mitigate the high forces imposed during downhill loaded walking. This study contributes to the understanding of gait and the reduction of biomechanical stress placed on the body during downhill walking.

KEYWORDS: load carriage, kinetics, peak loading rates.

INTRODUCTION: Load carriage systems (LCS) provide an important means of transport for equipment and supplies over long distances and unpredictable terrain, especially in a military application. LCS can significantly impact soldier performance and combat readiness and therefore an understanding of the physiological and biomechanical impact on the soldier is crucial in preventing injuries and enhancing performance. The majority of previous load carriage research has focused on physiological effects but more recently there has been a shift in focus to the biomechanical considerations. There is a lack of evidence however explaining the linear kinetics of walking downhill with a load and how this compares to walking level and uphill. Increases in ground reaction forces (GRF) and changes to the typical gait pattern as a result of additional loads and change in gradient have been linked to the cause of overuse injuries such as shin splints, blisters and stress fractures (Birrell & Haslam, 2010).

METHODS: Sixteen soldiers (14 males and 2 females) walked on an instrumented treadmill at speeds of 4km/h and 5km/h with and without a load added to their backpack frame at decline (-10%), flat (0%) and incline (+10%) gradients. The load consisted of a military type backpack external frame with shoulder straps and a hip belt and 35kgs of barbell weights placed between the shoulder blades at the level of the 4^{th} thoracic vertebra. The Bertec Instrumented Treadmill was used to obtain the ground reaction force responses of the soldiers. However, this paper will only discuss the linear kinetics during downhill walking. The participant's kinetic data were normalised and expressed as Newton's per unit body mass. In the loaded condition, the additional mass was added to the body mass and then normalised. Because the Fz GRF refers to the "vertical" force bound to the treadmill surface for the Instrumented treadmill, the Fz force remains perpendicular to the walking surface of the force plate regardless of the angle of the treadmill. The actual vertical GRF was therefore calculated from the Fz and Fy GRF components. The equations used for 10% incline and $10^{\%}$ decline surfaces were as follows:

- Incline vertical GRF = Fz cos5.7^{o} – Fy sin5.7^{o}
- Decline vertical GRF = Fz cos5.7^{o} + Fy sin5.7^{o}

Statistical analysis of the results involved a repeated-measure ANOVA to determine whether or not there were any statistical differences between the conditions. Tukey post-hoc tests were used for further analysis of the significant differences. Statistical significance was accepted at the level of p<.05 and all statistical testing was conducted using STATISTICA v.12.0.

RESULTS: Decline walking resulted in significant increases in peak loading rates, impact peak loads, braking forces and significant decreases in propulsive forces when compared to level and incline walking. Decline walking resulted in the first peak GRF to be 11% higher than incline walking and the second peak GRF to be 16% lower than incline walking. Walking at 5km/h compared to 4km/h resulted in significant increases in peak loading rates and impact peaks. The peak loading rates, vertical impact peak and anterio-posterior braking forces were significantly lower during the loaded condition compared to the unloaded condition during downhill walking. In addition, the first half of the stance phase was found to be significantly longer when carrying a load during level and decline walking which explains the reduction in forces during load carriage.

DISCUSSION: Uphill walking is significantly more physiologically taxing than downhill walking and therefore a key factor in regulating walking speed during military route marches. However the significantly larger GRFs measured during downhill walking suggest that a reduction in speed can be used as an effective strategy in reducing these high forces and risk of injury. Based on Newton's 2nd law, a greater impact peak (vertical axis) will be generated due to increased velocity of the body caused by gravity of the centre of mass towards the ground at heel strike (Birrell & Haslam, 2008). The no-load condition elicited significantly higher impact peaks compared to the load condition during downhill walking. This trend was also observed during level walking; however during incline walking there was no evidence to indicate that compensatory techniques are adopted to mitigate force. The findings from this study highlight the importance of pacing strategies as an effective technique to mitigate forces especially during loaded downhill walking. An increased stance time was evident during load carriage when walking downhill suggesting that individuals adopt protective mechanisms to mitigate additional force. Additional strategies such as increased muscle activation; greater joint flexion and postural adaptations may also be used to increase absorption of force when carrying additional loads. LCS design should focus on reducing the impact peak and maximum braking force as this has been strongly associated with the development of acute and overuse injuries (Birrell & Haslam, 2010).

Thrust maximum force was significantly higher for the no-load condition during level, incline and decline walking. This may be due to greater active momentum while carrying a load as opposed to no-load. Decline walking had significantly lower average thrust maximums which were to be expected because less force was required to propel the mass forward due to the gravitational force acting downwards and contributing to the forward momentum. Birrell and Haslam (2008) suggest decreased maximum thrust due to reduced extension of the knee during push off phase.

Decline walking resulted in significantly higher braking force compared to incline and level walking. Greater velocity at heel strike occurs during downhill walking which results in greater braking forces required to slow down the body (Birrell & Haslam, 2008). Incline walking resulted in a significantly lower braking force compared to level walking. The braking force was significantly higher during the no-load condition during decline walking. Knapik, Harman, and Reynolds (1996) found that increased sheer force caused by the braking force, acting at the foot-boot interface increases the chance of blisters. Birrell and Haslam (2010) found that braking forces can be reduced by carrying the load more evenly around the trunk. Braking forces have been found to be strongly associated with the development of acute and overuse injuries (Birrell & Haslam, 2010) and therefore when designing LCS emphasis must be placed on minimizing braking forces during decline walking specifically.

The propulsive peak is a positive force which acts in the anterior-posterior axis and is the inverse of the braking force where there was significantly less force required during decline compared to level and incline walking. Significantly less force was required during the load condition during downhill walking because there was greater momentum due to the additional load to propel the individual forward. Incline walking requires significantly more propulsive force to act against gravity.

CONCLUSION: During military route marches, the walking pace is regulated according to physiological cost such that speed increases on a decline and decreases on an incline in order to maintain the required average speed. However the biomechanical forces associated with musculoskeletal and overuse injuries are significantly higher during downhill walking and these forces are exacerbated as speed increases. The findings from this study highlight the importance of pacing strategies as an effective technique to mitigate forces during a military route march especially during loaded downhill walking. An increased stance time was found during load carriage which is supported by other studies (Birrell, Hooper, & Haslam, 2007; Birrell & Haslam, 2010) and suggests that individuals adopted a compensation strategy to mitigate additional force. Additional strategies such as increased muscle activation and greater joint flexion may also be used to increase absorption of force when carrying additional loads. Compensation techniques such as reducing walking speed and adapting posture to increase absorption of forces were found to be effective in mitigating force. These findings can be used to provide recommendations on safe load carriage practices to the military in order to enhance soldier performance and reduce the risk of injuries to the lower body.

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