EFFECTS OF BALLISTIC EXTREMITY ARMOR ON JOINT KINEMATICS DURING GAIT

1,2 Albert A. Adams, 1Leif Hasselquist, 1Jeffrey Schiffman

1 Natick Soldier Research, Development and Engineering Center, Natick, MA, USA
2 Worcester Polytechnic Institute, Worcester, MA, USA

email: albert.adamsiii@us.army.mil

INTRODUCTION

In addition to the standard armor vest, the U.S. military has been issuing ballistic armor designed to protect the arms and legs. Some of these extremity armor systems allow for scalable protection, providing soldiers with increased ballistic armor coverage when deemed necessary by adding additional components that protect the forearms and shanks to the upper arm and thigh components with hook and loop straps. Few studies have investigated the effects of extremity armor on gait, and none have included joint kinematics in their analysis. Hasselquist et.al (2008), previously reported that in both walking and running, VO2 increased significantly when any extremity armor was worn, as compared to a no armor condition. Researchers have also shown that walking with added mass reduces the stability of the leg kinematics and possibly the overall balance of the walking pattern [2]. Existing research on limb loading provides clues as to what gait effects may be expected with varying levels of armor applied to the limbs. Researchers have found loading the legs increases stride length and swing time [3]. It has also been found that in addition to the mass, the distribution of the load applied to the limbs has an effect on gait kinematics, with more distal loading resulting in greater increases to stride length and swing time [4]. The purpose of the current study was to characterize the joint kinematics of a scalable extremity armor system on gait, minimize its impact on gait and aid in the design of future armor systems. It was hypothesized that the wearing of the distal extremity armor components would alter joint kinematics during gait, as compared to both wearing no armor and wearing only the proximal armor components.

METHODS

The extremity armor system tested composed of a standard military helmet and armor vest (21.2 kg), upper arm and thigh components (3.6 kg), and removable forearm and shank components (2.0 kg). Twelve U.S. Army enlisted men participated in the study (mean 21.7 yrs; 1.78 m, 85.1 kg). The study was completed in accordance with Army Regulation 70-25 (Use of Volunteers as Subjects in Research). Subjects were asked to walk (1.34 m/s) and run (2.46 m/s) on a level treadmill (AMTI, Watertown, MA, USA) with each of three different levels of extremity armor coverage: a no armor (NA) condition (2.0 kg) that consisted of minimal clothing, combat boots, and a helmet; a partial extremity armor (PEA) configuration (24.9 kg) that consisted of an armor vest and extremity armor on the upper arms and thighs in addition to clothing worn in the NA condition; and a full extremity armor (FEA) configuration (26.9 kg) that consisted of forearm and shank armor in addition to the PEA configuration. After 5 min on the treadmill, 20 sec of kinematic data was collected (Qualisys Medical AB, Gothenburg, Sweden). From the kinematic data collected, trunk, hip, knee and ankle angles, as well as temporal gait measures, were calculated for 10 consecutive strides and averaged for each trial (Visual3D, C-Motion Inc., Germantown, MD, USA). Joint angles were normalized to each participant’s anatomical neutral standing position. One-way repeated measures ANOVAs (α=0.05) were performed for all variables.

RESULTS AND DISCUSSION

In walking, PEA and FEA conditions resulted in significant changes to hip, knee, and ankle ranges of motion (ROM), compared to NA (Table 1). The PEA and FEA conditions resulted in a decrease in mean maximal plantar flexion per step, and an
increase in maximal dorsiflexion, maximum knee flexion, maximum hip flexion. No statistically significant differences were found in walking between the effects of the PEA and FEA. This may indicate that the forearm and shank components of the FEA were not heavy enough to elicit effects on gait when added. The increases in hip and knee ROM, as well as an observed increase in double support time in walking, are similar to standard backpack load carriage [5]. The volunteers may have adopted a gait strategy based on the torso armor load which weighed 20 kg and the extremity loading may have been negligible after that weight point. In running, hip flexion, hip extension, dorsiflexion at the ankle, and trunk ROM were increased by use of armor in the PEA and FEA conditions, while plantar flexion at the ankle decreased. Such a decrease in plantar flexion could not be found in any previous load carriage or extremity loading literature, and warrants further investigation.

When looking at total joint ROM in running (Table 1), the reduction in maximum plantar flexion nullified the increased dorsiflexion, preventing the ankle ROM from reaching a significant difference. Only the hip and trunk displayed a significant increase in total ROM resulting from the PEA and FEA, as compared to running with the NA condition. Such an increase in hip ROM is also typical of torso loading during running [6], and points to the mass of the vest overpowering potential effects of the extremity armor. No changes in temporal running kinematics were found between armor conditions.

<table>
<thead>
<tr>
<th>Armor Condition</th>
<th>Walking ROM</th>
<th>Running ROM</th>
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<tbody>
<tr>
<td></td>
<td>Lean</td>
<td>Ankle</td>
</tr>
<tr>
<td>No Armor</td>
<td>3.588* (0.806)</td>
<td>27.965* (3.390)</td>
</tr>
<tr>
<td>Partial Armor</td>
<td>4.721 (1.542)</td>
<td>23.374 (2.814)</td>
</tr>
<tr>
<td>Full Armor</td>
<td>4.015 (0.935)</td>
<td>24.698 (2.322)</td>
</tr>
</tbody>
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* Asterisks (*) indicates significant difference from other armor conditions (α<0.05).

CONCLUSIONS

Wearing of the extremity armor system used in this study was found to alter joint kinematics of walking and running, compared to walking and running unarmored. Contrary to our hypothesis, no significant changes in the joint kinematics were found between the effects of the PEA and FEA conditions, which may be partly due to the low mass of the distal armor components. Other researchers have shown that added body mass of up to 30% of body weight had only small changes on sagittal plane joint kinematics [2]. However, that study only addressed total body mass changes.

For soldiers, this study indicates that there would be no biomechanical benefit to removing the distal components of the extremity armor system. The altered joint kinematics may interact with the impact of the energy cost of weight while wearing the FEA. Stability and balance during ambulation may also be affected due to the added mass and changes in the joint kinematics. The results of the current study are limited to the specific extremity armor system tested, but demonstrate the need for further investigation into the biomechanical effects of load placement on the limbs and the interaction effects of limb loading and torso loading.

REFERENCES