

Biomechanical Evaluation of Headwear System Prototypes using Digital Human Modeling

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ABSTRACT

Digital human modeling allows for the evaluation of equipment designs before physically building and testing prototypes. This paper presents an example of how digital human modeling was used to perform biomechanical studies on four new designs for future infantry headwear systems. Range of Motion (ROM) and cervical spine forces and moments were compared using static and dynamic simulations in a virtual environment. Results confirmed that headwear system prototypes with optimal overall mass and Centre of Mass (CM) location, as determined by previous human subject trials, exerted the least amount of biomechanical loading. Facial protection was favorable when considering forces and moments in the cervical spine, however when considering ROM, the rigid prototype mandible guards used in this evaluation are not recommended. The shape of a more accommodating mandible guard was developed, and the option to remove facial protection for some tasks was recommended.

INTRODUCTION

When considering biomechanical studies involving assessment of weight and equipment borne by the human, digital human modeling can be used for a non-invasive, repeatable method of investigating ROM and muscle motor control without intricate laboratory equipment and numerous test subjects. For this study, the software program Digital Biomechanics by Boston Dynamics was used to evaluate helmet prototypes while being benchmarked against the in-service Canadian helmet (CG634), the in-service United States Marine Corps (USMC) helmet, and the human head alone. The

software provided a means of analyzing ROM and mass properties of the helmets under static and dynamic loading conditions.

BACKGROUND

The aim of the SIHS (Soldier Integrated Headwear System) program is to determine the most promising headwear concept that significantly enhances the survivability and effectiveness of the future Canadian soldier by developing, evaluating, and demonstrating novel concepts for integrating enhanced protection, sensing, information display, and communications technologies into a headwear system. Based on the results of the SIHS conceptual design phase, four helmet concepts (Alpha, Bravo, Charlie, and Delta) were developed [1]. Figure 1 presents the four prototype headwear systems with the digital human in the virtual environment.



Figure 1: Headwear System Prototypes (top left to bottom right - Alpha, Bravo, Charlie, and Delta)

The headwear systems incorporated visors, mandible guards, and cheek plates for blast protection. Cameras and visual sensors were incorporated with visual displays at eye level. Enhanced hearing systems were included as well as various sensors, communications technologies, and ventilation systems. Bulk, complexity, and weight presented challenges for ergonomic performance requirements, and facial protection needed to allow a maximum Field of View (FOV). The prototype headwear systems had a higher mass (approx. 2.3 to 2.7Kg) than the in-service helmets (approx. 1.5Kg). Prototypes Bravo and Charlie weighed slightly more than Alpha and Delta. It should be noted that Tack et. al. [2] used human subject testing to determine that 1.5Kg, 2.0Kg, and to a lesser extent 2.5Kg weighted helmets were the preferred values for overall mass, while the 3.0Kg was the least preferred.

A comparison of the CM locations on the sagittal plane is shown in Figure 2. The origin (0,0) is at the atlas (C1) and the ellipses represent 95% confidence values for the preferred location of the CM according to Tack et. al. [2]. As shown by the ellipses, the preferred CM location was dependant on the mass of the supported load, with the 3.0Kg condition ranging slightly lower (i.e. closer to the atlas) than the 2.0 and 2.5Kg conditions.

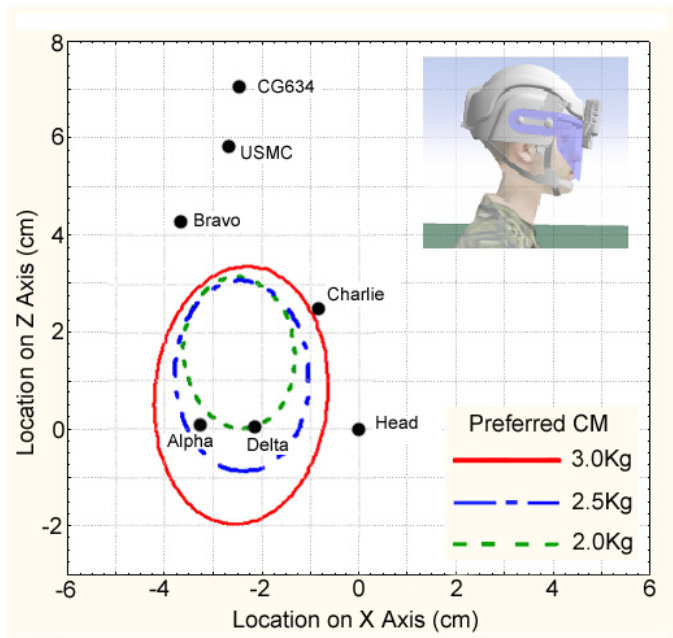


Figure 2: CM Location with respect to the Preferred CM Location

The CM of prototype Alpha and Delta were within the preferred position for a 2.5Kg helmet. They had a much lower CM position than the other headwear systems likely because they incorporated mandible guards. All prototypes had lower CM positions than the in-service helmets because of the additional components. The X, Y, and Z axes used in this study are shown in Figure 3.

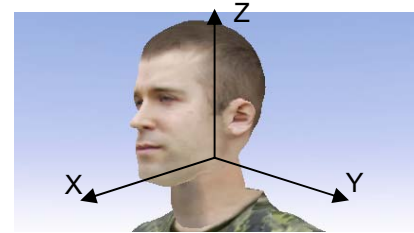


Figure 3: Axes and Origin at the Altas (C1)

METHOD

An 18 segment digital human model was configured, and solid models of headwear system prototypes were incorporated by importing a 3D graphical representation and inputting the mass properties of each component. Mass properties included total mass, CM location, and the mass moment of inertia tensor (a 3x3 matrix that considers inertias of a solid in 3D space). Next, the human model and the various headwear systems were compared by considering ROM, static positions, and dynamic simulations.

RANGE OF MOTION - An iterative learning technique was used to determine the neck ROM in the virtual environment. In-vivo motion capture data was used to generate an elliptical rotation of the digital human model's head. With subsequent iterations, the trajectory was expanded to explore a larger ROM. The trajectories were limited by collision interference or by joint limits. Phase plots of the CM of the head in the transverse (XY) plane were produced to visualize the ROM, and a normalized score was used to compare the difference between the prototypes. The mathematical definition of the normalized score is the area of the final trajectory divided by the area for the full range of motion as specified by the joint limits. Figure 4 depicts a phase plot of the human head on it's own without any constraints. The normalized score is 1.0. With the constraint of prototype Alpha (helmet and mandible guard) the normalized score was less than 1.0 (Figure 5).

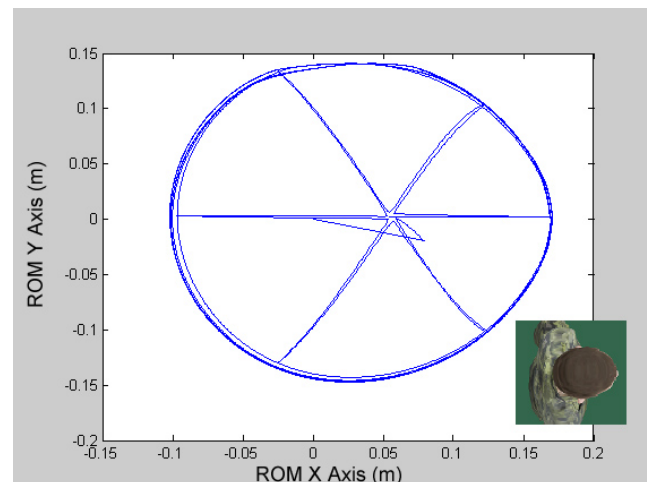


Figure 4: ROM Phase Plot with No Constraints

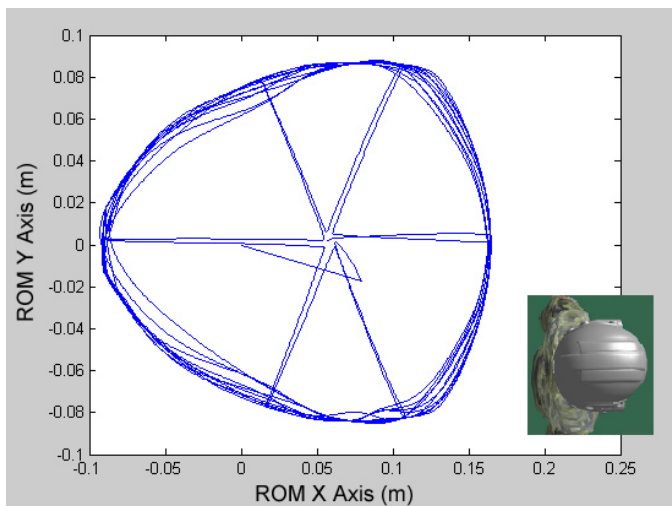


Figure 5: ROM Phase Plot with Prototype Alpha

Next, ROM was analyzed for the various headwear conditions with the digital human wearing a Canadian Generation III fragmentation protective vest and a large rucksack. Finally, the digital human was positioned in various firing positions while aiming the Canadian (C7A1) assault rifle.

STATIC ANALYSIS - Digital Biomechanics was configured to evaluate the static forces and moments about the cervical spine at the Atlas (C1). Solid models of the helmet prototype components were attached to the digital human model. The static forces and moments were generated by scripting the character to pose still (i.e. static, isometric loading of muscles) in a chosen upright position, sagittal extension, sagittal flexion, and coronal flexion (Figure 6) while gravitational forces were applied to the entire virtual environment. A comparison of the four prototypes and benchmark conditions was made.

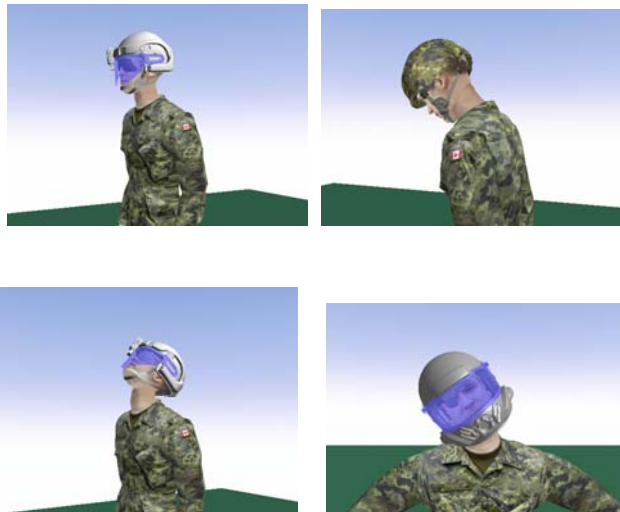


Figure 6: Static Positions Chosen for Analysis (top left to bottom right – Upright, Sagittal Flexion, Sagittal Extension and Coronal Flexion)

In an upright position, the gravitational force created a positive moment about the Y axis (i.e. loading the dorsal muscles of the neck). In sagittal flexion, gravitational force also created a positive moment about the Y axis. In sagittal extension, gravitational force created a negative moment about the Y axis (i.e. loading the ventral muscles of the neck). While in coronal flexion, the gravitational force created a positive moment about the X axis when posing with the head to the right, and a negative moment about the X axis when posing to the left. Since design configurations and equipment mounted to the sides of the helmet could potentially yield unsymmetrical loading in the coronal plane, both sides were tested.

Static Fatigue Limits - A wealth of information on the biomechanical properties of neck specimens indicates that neck injury or fatigue is very dependent on the orientation of the head, the type of loading on the neck, and whether the loading is static or dynamic. Since the head was maintained in a specific position for static poses, this analysis was a form of isometric exercise. It was found that the strength of muscles required for these static poses would not be likely to reach an injurious level, but could be related to a fatigue limit presented by Phillips and Petrofsky [3], who showed that when sustained contractions begin to exceed 15% of the individual muscle's maximum voluntary contractions (MVC), the tension in the muscle will become fatiguing. By considering 15% of the MVC for neck muscles in the various static positions [4, 5], fatigue limits were established. Furthermore, Meltzer and Moffitt [6] published a summary of results showing the endurance times, in minutes, that the neck muscles are likely able to contract until complete fatigue once they cross the 15% MVC threshold. Therefore, for this study, when a prototype in a specific static pose surpassed the fatigue limit, a time was estimated that the stance could be held.

DYNAMIC ANALYSIS - The prototype helmets were attached to the digital human model and dynamic forces and moments were evaluated for rotation of the head, jumping from a 1m platform, walking, and running. Gravitational forces were applied to the virtual environment throughout the dynamic tasks.

Rotation of the Head - The human model was scripted to perform a rotation of the head about the X axis, Y axis, and Z Axis. Without a helmet, the neck muscles were required to apply the least amount of axial torque. When the headwear systems were added to the model, a higher amount of torque was required in the neck muscles to achieve the same dynamic results. The various headwear systems and benchmark conditions were compared by considering the difference between the applied torques.

Jumping from a 1m Platform - A dynamic analysis was performed on a jump from a 1m platform simulation. The script for the human model involved the jump motion as well as landing on the ground.