Modeling Ability to Perform Common Soldier Tasks Based on the Army Combat Fitness Test Deadlift

Laura A. Frey-Law, Rajan Bhatt, Russell Schneider, Guillermo Laguna Mosqueda, Marco Tena Salais, Landon Evans, and Karim Abdel-Malek

Virtual Soldier Research Team, Iowa Technology Institute, The University of Iowa

Introduction

The US Army has developed a battery of physical fitness test events to measure soldier readiness to engage with and overmatch the enemy in close combat. The original Army Physical Fitness Test (APFT) only assessed three events: a two-mile run, push-ups, and sit-ups. To better represent the myriad of physical tasks soldiers are exposed to and expected to complete, a new Army Combat Fitness Test (ACFT) was developed (US Army, 2018). The ACFT comprises six physical exercise tasks: (a) three-repetition maximum deadlift; (b) standing power throw; (c) hand-release push-ups; (d) a combination sprint, drag, and carry task; (e) leg tuck (or plank); and (f) two-mile run. The Army performed several investigations comparing task performance of the ACFT to a simulated battle drills and common soldier tasks (CSTs) obstacle course, where completion time was the primary outcome measure. However, the Army was not able to compare more detailed aspects between CSTs and the new ACFT, such as biomechanical analyses based on digital human modeling.

CSTs and battle drills represent the wide range of tasks that may be expected as part of any soldier's day, ranging from sedentary, desk-based work to vigorous tasks such as marching in full gear or having to extract and transport soldiers in battle. The goal of the ACFT was to assess multiple physical domains, including strength, power, endurance, oxygen consumption, and energy expenditure, to represent the more physical components of CSTs to ensure they would be capable of completing these tasks as well as reduce the risk of injury.

The work presented here is part of a bigger project in which the Iowa Technology Institute's Virtual Soldier Research (VSR) lab simulated and analyzed the ACFT test events and several moderate- to high-demand CSTs. The aim of this paper is to compare the strength requirements at several major joints based on advanced inverse dynamics and digital human modeling between one of the ACFT tasks, the deadlift, and several more demanding CSTs (Abdel-Malek, 2008; Xiang, 2010). We focused on two primary questions:

1) Is the ACFT predictive of CSTs?
2) Are the minimum ACFT event standards sufficiently rigorous to meet standard CST requirements?

Methods

Six Army Reserve Officer Training Cadets (ROTC) students (3F, 3M) were recruited to complete a series of ACFT and CSTs with motion capture over three visits. However, 1 female did not complete the study, thus only 5 subjects' data are considered for these analyses. All participants provided written informed consent, as approved by the Institutional Review Board (IRB). ROTC students were recruited in order to ensure some level of familiarization with Army testing and maneuvers (see below for more detail). The motion capture data was then transferred to the Iowa Technology Institute Santos simulation engine and processed using the advanced inverse dynamics algorithms developed by the research team at VSR. Using the Santos® and Sophia® DHMs, joint torque profiles (i.e., estimated workloads) were modeled. Peak torques were extracted for each task for the knee, hip, truck, shoulder, and elbow. Values were compared across tasks.

Motion Capture

Motion capture (Thewlis, Bishop, Daniell, & Paul, 2013) of all tasks were performed using OptiTrack, with the Motive software. Study participants wore a black bodysuit with fifty-five 9 mm infrared markers attached with velocro following a customized markerset protocol (Rahmatalla, 2011) that our team had previously developed to work with the proprietary Santos program (see Figure 1). For all ACFT events, the body suits were worn over clothing that closely resembled the standard Army Physical Fitness Uniform (APFU): t-shirt, shorts, socks, and running shoes. This allowed the participant to have a full range of motion while conducting the data capture. The motion capture suit is a combination Spandex and Velcro suit that allowed the motion capture team to attach sensors on the body at prescribed locations. The suit included a top, pants, and covers that go over the shoes that allow the sensors to be placed on the feet. During the ACFT portion of the study, the participants also wore a cap of the same material that allowed sensors to be placed on the head. To ensure proper labeling of the markers, the participants were instructed to start and end in T-pose with their arms extended to the side and palms facing downward. This position allowed for all the markers to be visible to the Motive program as well as allowing the motion capture team to properly label the markers while processing the data.

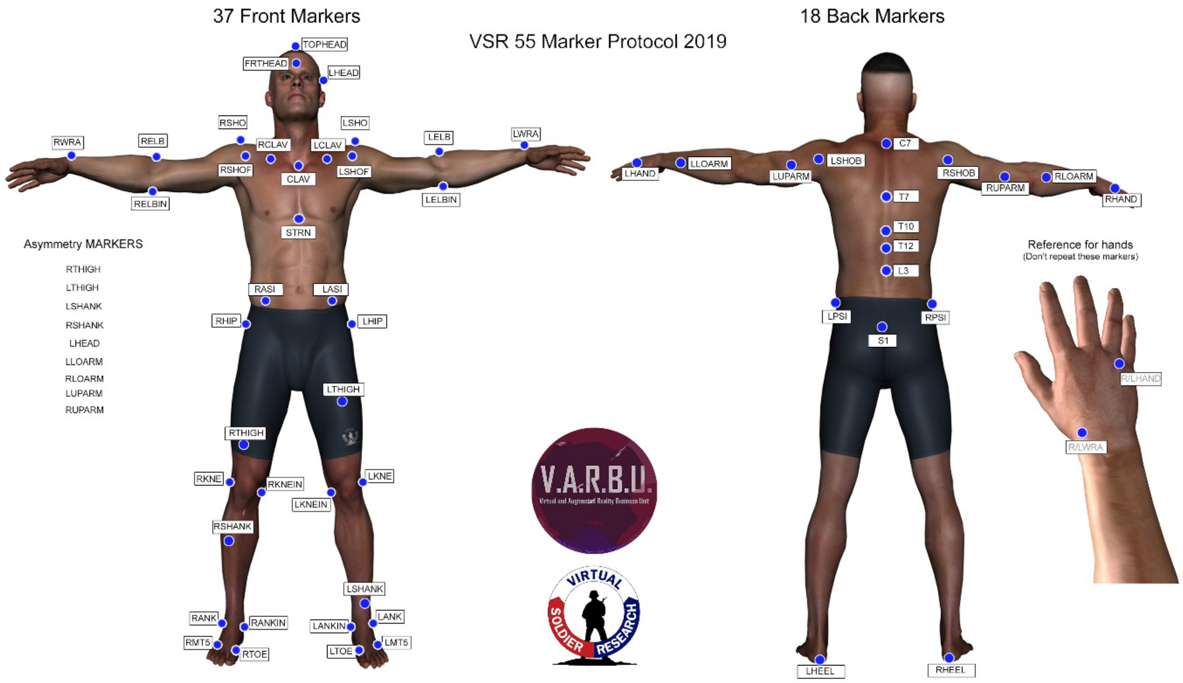


Figure 1. Markerset protocol developed for use with Santos proprietary software for motion capture analysis with OptoTrack.

Twelve OptiTrack Flex 13 cameras were used to capture and track the markers via infrared light during the ACFT and CST tasks. Figure 2 shows the layout of the cameras in the laboratory space. In addition to motion capture, video recordings of the tasks were made to document the movements for later reference as needed. For the larger study, a few of the tasks were collected in an alternate venue, a racquetball court, due to height limitations in the laboratory; however, for this report, none of these tasks were needed.

During the CSTs portions of the data capture phase, participants were sometimes required to wear additional items as used by regular Army soldiers, either as “fighting load” or “sustainment load.” The fighting load consists of body armor or armor plate carrier with pouches, the Army Combat Helmet (ACH). which replaces the beanie worn during the ACFT portion, and an inert rubber dummy M-4 rifle. The motion capture team utilized a plate carrier instead of the Army Improved Outer Tactical Vest (IOTV) due to the analysis of the plate carrier being more widely used and issued to Army soldiers as a replacement for the IOTV. As prescribed in Army Technical Manual 10-8465-236-10, the plate carrier consisted of the plate carrier itself with front, back, and side plates. The external pouches were added to the plate carrier to simulate the average weight that a soldier would carry into a battle. The pouches included the following: (a) two 3-slot M4 magazine pouches, (b) pouch with two DUMMY grenades, (c) 3-liter hydration pack on back, (d) Individual First Aid Kit (IFAK), and (e) radio pouch.

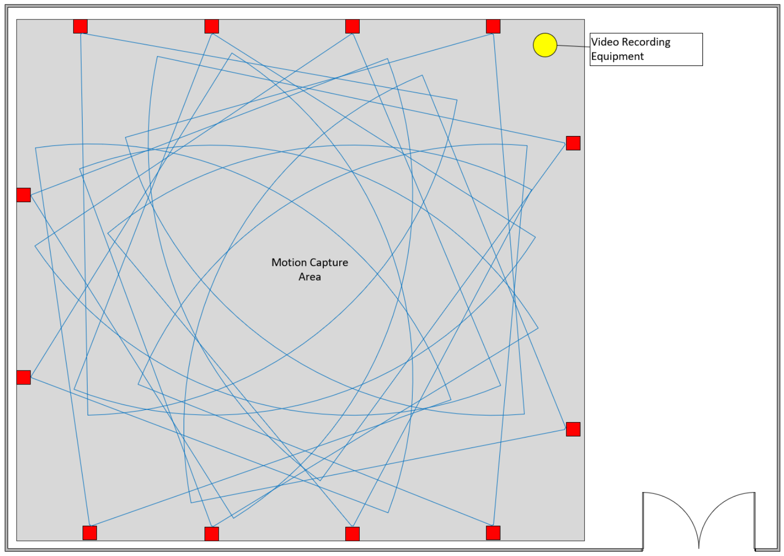


Figure 2. Layout for collecting motion capture data of the deadlift and several CSTs. The cameras are represented by red squares. The orientation of the cameras is shown as blue arcs converging in a central area of the motion capture area. The yellow circle represents the location of video recording equipment used to record the tasks being completed for reference.

Three sizes of body armor were available to accommodate different body types, but all weighed approximately 17.3 kg (38 lbs). The helmet weighed 1.4 kg (3 lbs) and the dummy rifle was 2.5 kg (5.6 lbs). The fighting load configuration is shown in Figure 3. The “sustainment load” consists of all fighting load gear with the addition of a 23 kg (45.9 lbs) rucksack (see Figure 4). Thus, the total added weight of gear under the sustainment load was approximately 42.3 kg (93 lbs).

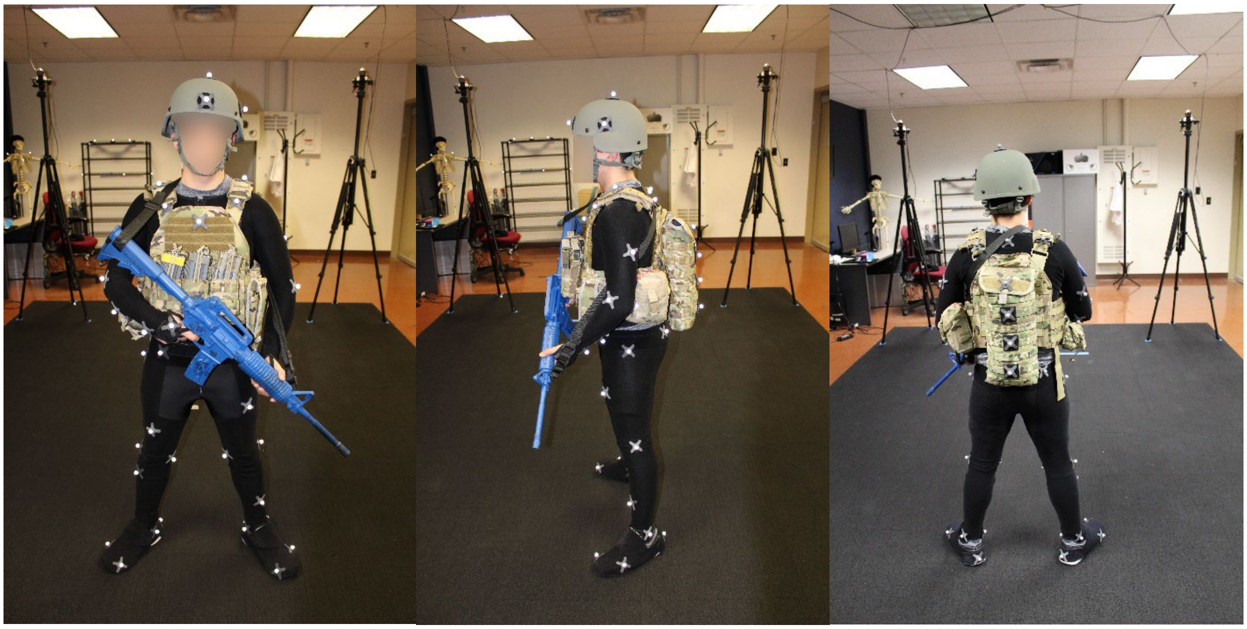


Figure 3. Participant with "fighting load" configuration during motion capture sessions for select CSTs, wearing the "small" vest.

Figure 4. Participant with "sustainment load" configuration during motion capture sessions for select CSTs.

Deadlift

The hexagon deadlift bar with weight plates ranging from 4.5 – 20.5 kg (10 – 45 lbs) was provided by Rogue fitness. While the ACFT standard is to perform a three-repetition maximum for deadlift, for the purposes of human subjects' safety and approvals, a maximum of 31.8 kg (70 lbs) was used. The minimum weight requirement for passing the deadlift portion of the ACFT is 63.6 kg (140 lbs) across men and women at the time of this study; thus, during the DHM simulation phase of this study, the applied weight was assessed as 63.6 kg when estimating joint torques.

The deadlift was performed by the participant standing in the middle of the motion capture area in a T-pose. A hexagonal deadlift bar was placed in front of the participant with the required amount of weight. When instructed, the participant lowered their arms and stepped into the hexagonal bar with their feet shoulder-width apart. They bent at the waist, hips, and knees and grasped the bar. After grasping the bar, the participant raised and lowered the bar three times, then stepped either backward or forwards out of the hexagonal bar and returned to the T-pose. The participant was instructed to not drop or bounce the bar on the ground, but to lower it in a controlled manner as they returned the weights to the ground (see Figure 5).

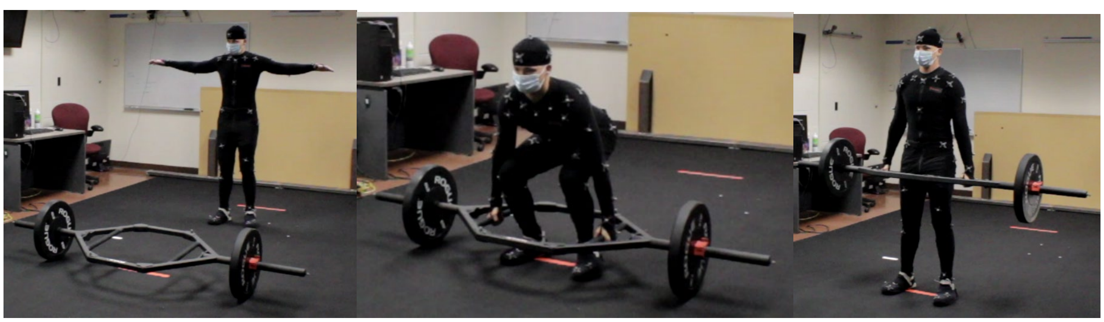


Figure 5. Example of the deadlift ACFT task as performed for motion capture purposes.

Common Soldier Tasks

Multiple CSTs were assessed as part of the larger study. For the purposes of these analyses, only a subset will be discussed: casualty extraction (horizontal and vertical extraction), high crawl, being in a fighting position, prone position with sustainment load, lift and carry sustainment load, marching with sustainment load, climb through 42" window or over 52" wall (see Figure 6A), jump over 18" obstacle, jump from 50" height, stack sandbags, and hand-to-hand grapple. To accomplish these tasks, several additional pieces of equipment were purchased, borrowed, or built, such as a fabric sled with pull straps and a SKED litter from the National Guard, for different types of casualty extraction, and vertical wall obstacles of various heights as needed.

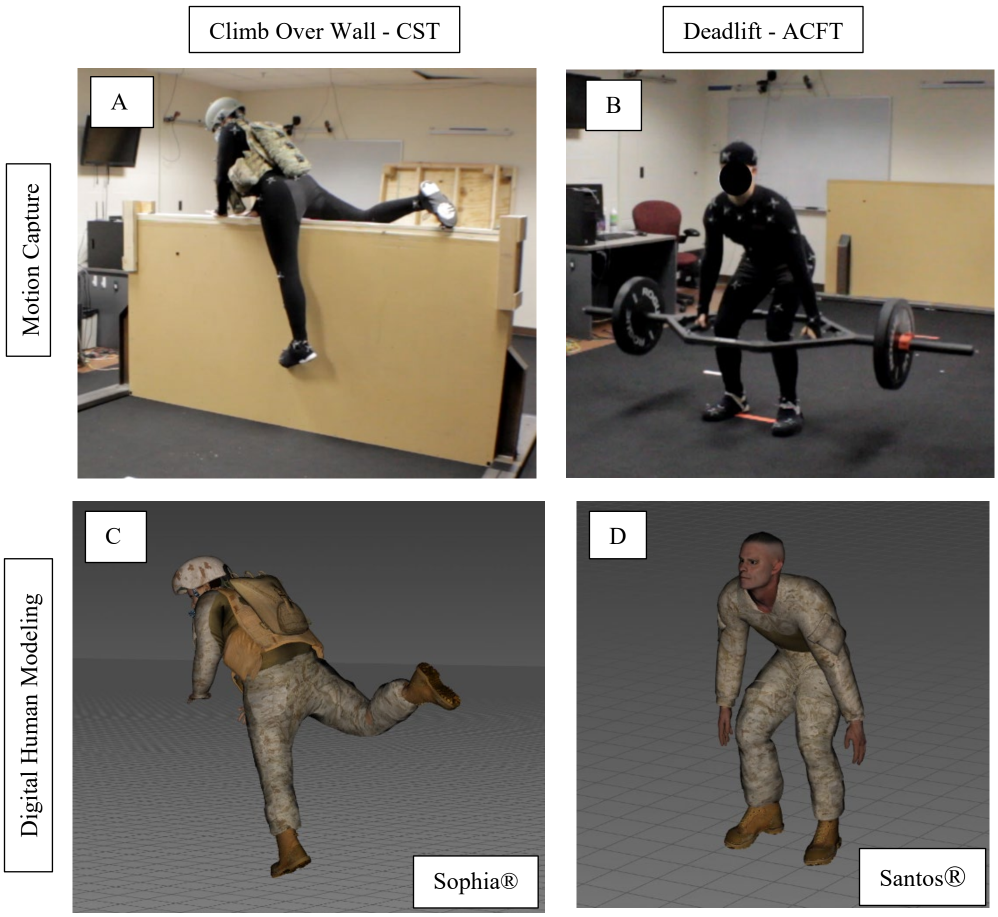


Figure 6. Two examples of transforming data from motion capture (A, B) to perform the workload analysis with digital human modeling (C, D).

Analyses

The motion analysis and digital human modeling was performed for the deadlift and multiple simulated CSTs for five major joints of the body: trunk (low-back extension and abdominal flexion), hip flexion/extension, knee flexion/extension, shoulder flexion/extension, and elbow flexion/extension. The ratio of the peak torque required to complete the CSTs relative to the torque required to complete the deadlift provides estimates of how challenging soldier tasks are relative to the strength needed to perform the deadlift at each joint, where 100% indicates equal levels of muscle strength is required for both. Ratios less than 100% indicate that the soldier tasks are less strenuous than the corresponding ACFT deadlift, and ratios over 100% indicate the CSTs require more strength than the corresponding deadlift (at the passing 60-point level, assuming 63.6 kg (140 lbs) lift). Means of peak torques and of ratios across all five subjects were performed using SPSS statistical software (IBM) to summarize findings. Lastly, values for men and women were considered separately to evaluate for apparent sex differences.

Results

Examples of single-subject ratios between the strength required to perform several CSTs and the deadlift are provided in Tables 1 and 2. Note in these two individuals, who represent a male and a female subject, respectively, that clear patterns are present. The deadlift requires more strength than does marching with a sustainment load or jumping over an 18" wall but is easier than performing a casualty extraction. While the movement strategies used by different subjects may differ, due to anthropometric differences, these overall patterns were notably consistent.

Table 1. Ratio of peak torques required to complete a series of CSTs relative to the Deadlift at passing level (male subject, 1.78m tall, 71.7 kg).

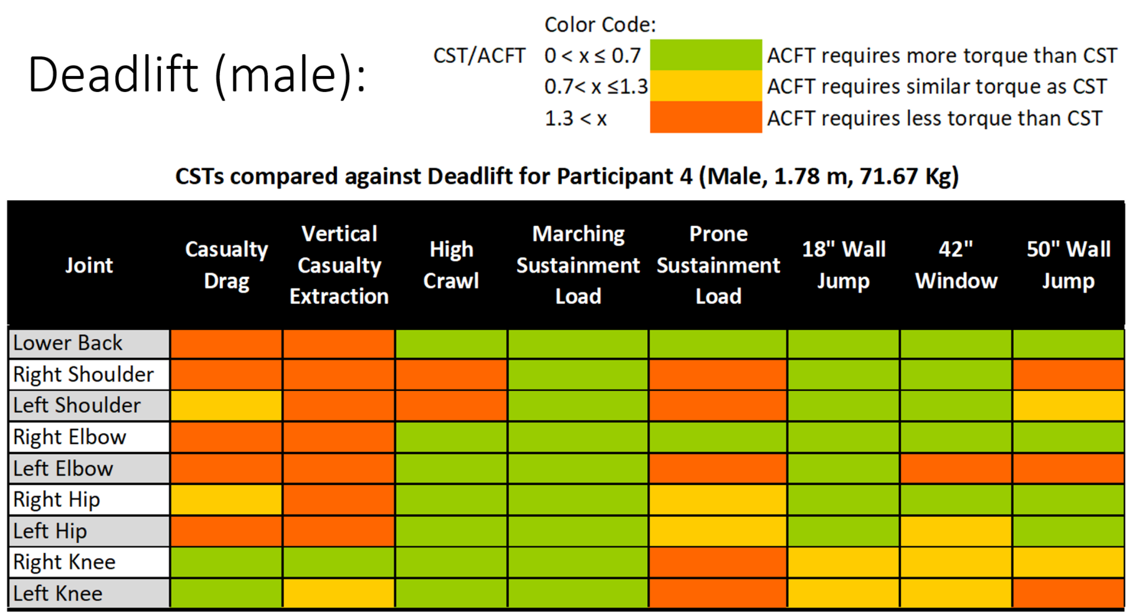
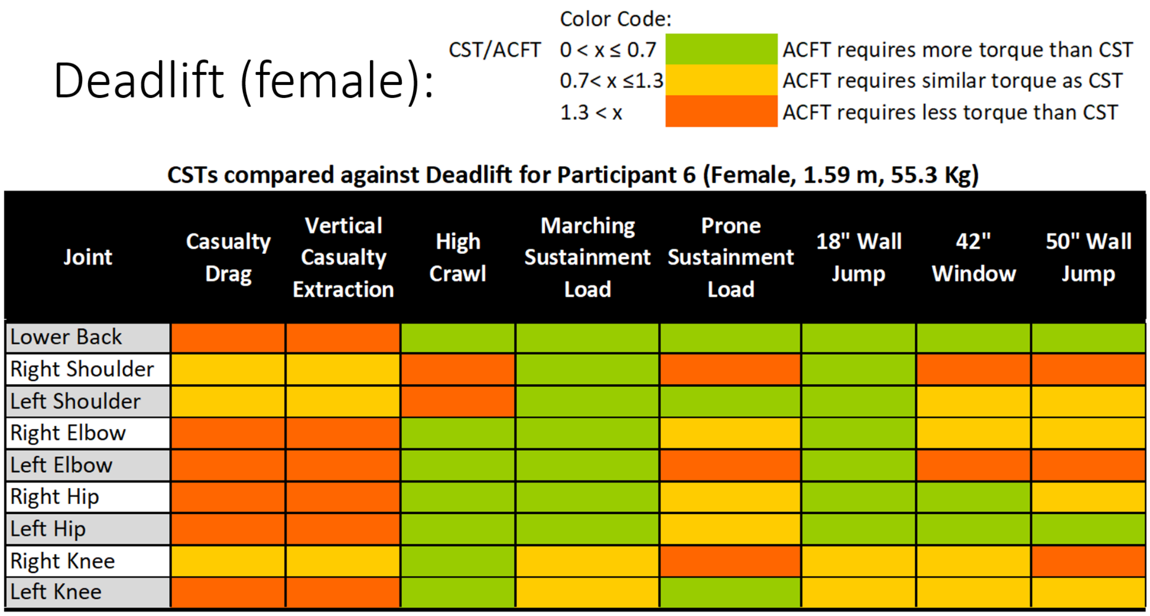


Table 2. Ratio of peak torques required to complete a series of CSTs relative to the deadlift at passing level (female subject, 1.59m tall, 55.3 kg).



When evaluating the averages across the five participants, the muscle force requirements for the deadlift often represent similar workloads associated with several of the more strenuous CSTs, yet are less than the tasks involving extracting casualties. See Figure 7 for the heat map of the ACFT deadlift versus eight of the CSTs assessed as an average of all subjects, for muscle groups most involved in the deadlift.

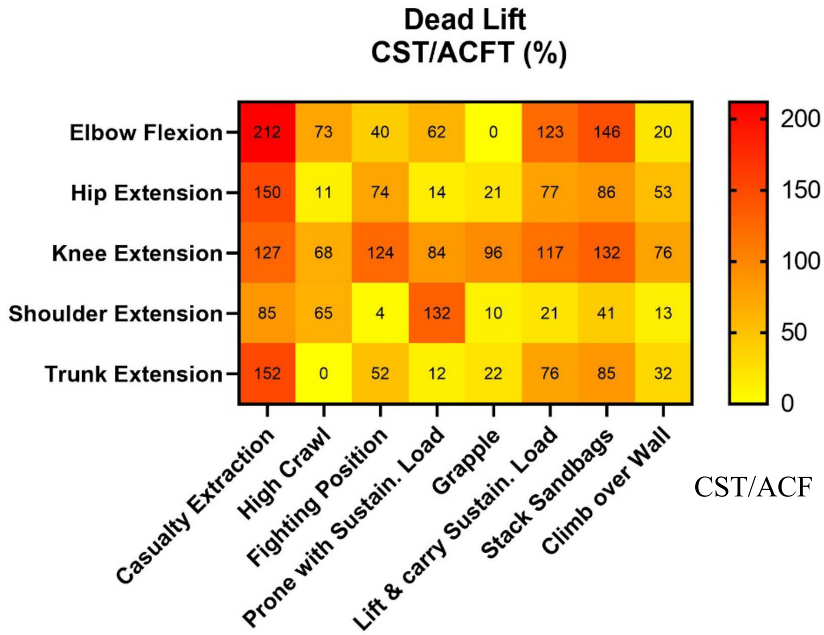


Figure 7. Heat map of the CST/ACFT ratio between muscle torque requirements, where >100% indicates the CST requires more joint torque than the deadlift at 60-pt level (140# - 3 rep max). Note: red = CST > ACFT strength needed; yellow = CST < ACFT strength needed; orange = approx. equal strength needed for CST and ACFT.

Similarly, Figure 8 highlights tasks which exceed the requirements of the passing deadlift level, involving most commonly the knee, but also the trunk and shoulder. However, the absolute torques needed to complete the ACFT deadlift and select CSTs (casualty extraction and stacking sandbags) are quite similar overall (Figure 9).

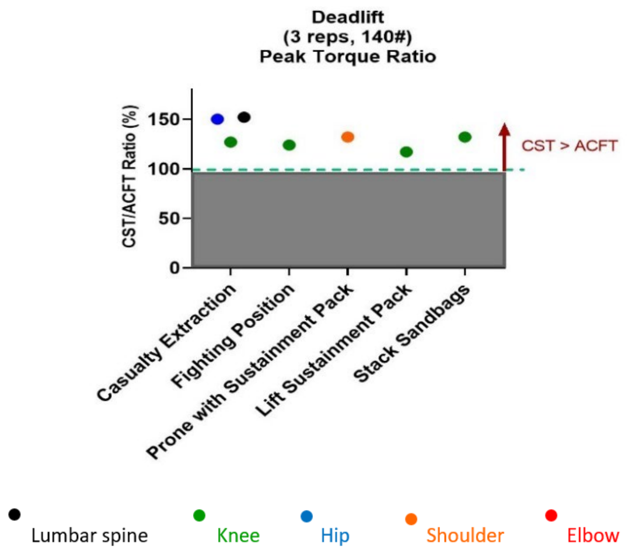


Figure 8. Force requirements for CSTs that exceed the ACFT deadlift (60-pt level), based on the ratios of the CST /ACFT peak torques (%). The colors indicate different joints.

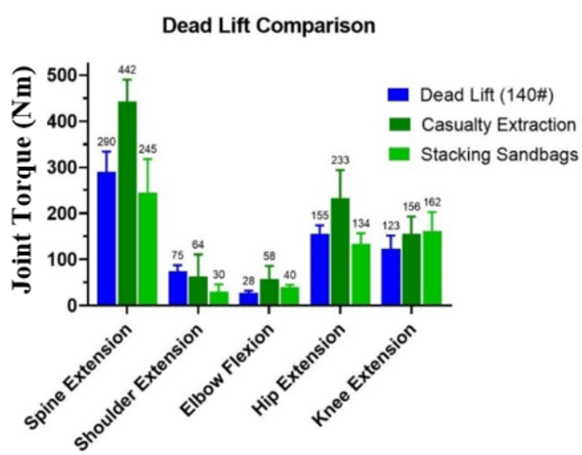


Figure 9. Mean (SD) torque requirements needed to complete ACFT deadlift in blue and two comparable CSTs (in green), considering the key joints involved.

When comparing the biomechanical strength requirements for the deadlift as well as CSTs (see Figure 10), minimal differences between the men and women were observed. Task requirements are not based on strength per se, but on body weight and height, movement speed, acceleration, and any additional external loads that must be lifted, moved, or carried. Further, some tasks can be performed in different manners, yet achieve the same goal, such as when lifting a load, one can place more load on the spine or the knees depending on the lifting strategy used. Accordingly, in general there is as much variation within, as there is between, men and women in terms of the joint torque requirements needed to accomplish CSTs as well as the ACFT deadlift.

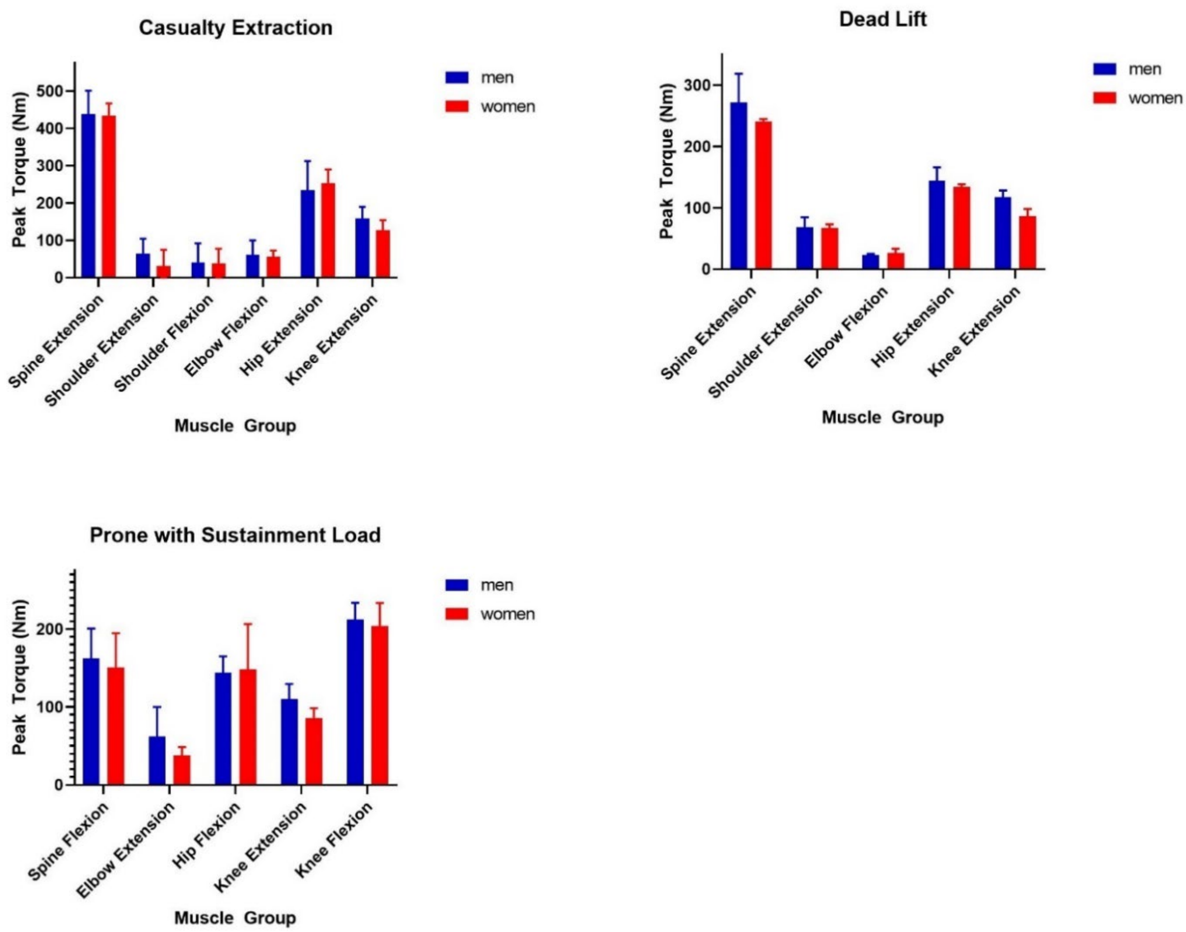


Figure 10. Mean (SD) torque requirements needed to complete 2 CSTs and the ACFT deadlift for the male (blue bars) and female (red bars) study participants. Note that there were no significant differences observed.

Discussion

The primary aim of this paper was to evaluate the biomechanical workloads associated with the ACFT deadlift and compare it to several simulated CSTs. Our modeling with Santos and Sophia DHMs demonstrates that the deadlift requirements at the passing level of 63.6 kg provides largely a good match for several major muscle groups and is even less strenuous than tasks involving casualty extraction and transfers. Accordingly, the deadlift, one of six ACFT tasks, provides a means to assess muscular strength that is relevant to the expected strenuous workloads for a soldier. That is, the peak muscle strength requirements to complete one of the casualty extractions, for example, required from 127 – 152% of the peak strength required for key muscles involved in completing three repetitions of the deadlift using 63.6 kg.

While prior efforts to validate the ACFT showed correlations with completion times of a battery of CSTs, this adds additional information targeting strength and task workloads. The use of DHMs in conjunction with motion capture methodology enabled us to make these analyses possible, as direct measures of task workload are not readily measurable otherwise. This application of DHM provides insights into which common soldier tasks most closely match the deadlift, the most strength-intensive of the ACFT tasks. This approach maps strength requirements needed to perform the various common soldier tasks at several major muscle groups to the strength needed to complete the deadlift. For a strength-dominant ACFT task, this analysis approach is very appropriate. Further, this mapping of strength requirements as a comparator to determine capability or potentially strength cut-points could be applied to other work-intensive environments.

The ACFT was developed to incorporate multiple physical fitness domains, such as muscle strength, endurance, aerobic capacity, power, speed, etc. The use of DHMs as described here to model peak torque requirements is particularly of use for assessing muscle strength domains of fitness. Other planned and ongoing analyses include assessing the development of muscle fatigue over time with repeated tasks, such as the hand-release push-ups, or the infleunce of performing multiple tasks serially while applying the revised three comparment controller (3CC-r) model of muscle fatigue (Xia & Frey-Law, 2015) (Looft, Herkert, & Frey-Law, 2018) (Looft, Herkert, & Frey-Law, 2018). The use of DHMs in combination with other models may provide similarly useful metrics for comparison when considering other domains of human performance.

These analyses involved both men and women and found that the strategies employed were largely similar. At the time of this study, the Army had defined cut-points for passing that were age- and sex-neutral. Our analyses supported that the loads required were indeed also largely gender-neutral. However, the relative requirements in terms of percent of peak capability indeed differed between men and women. That is peak strength is typically lower in women than men by approximately 40% based on normative data (Frey-Law, et al., 2012) (Hussain & Frey-Law, 2016). It is analyses such as these that may help provide the necessary data to help guide decision-making for the use of gender-specific vs gender-neutral physical performance metrics.

Limitations

Interpretation of this study must consider the following limitations. First, this current evaluation focuses on the strength domain when making comparisons between the deadlift and CSTs. While this may be ideal for the deadlift, it may not be as relevant to the other ACFTs, which may represent other fitness domains moreso than the deadlift. Second, due to the intensive nature of this data collection and analysis process, sample sizes for these types of biomechanical studies are typically small. However, the motion data collected from this cohort can be used to examine these tasks with digital human models of varying anthropometry. Third, technical aspects of modeling the large range of motion of the shoulder in 3-D space make the shoulder torque estimates prone to error, as flexion and extension planes can collapse with abduction and adduction planes, as well as issues of gimbal lock; thus, shoulder torques are at higher risk of error than the remaining joints assessed. This study also assumes that a change in parameters such as anthropometry and deadlift load would not change the manner in which a motion is performed. Lastly, traditional inverse dynamics analyses require force plates to assess normal reaction forces at the feet; however, the dynamic and varied contact sites inherent with several CSTs makes the use of force plates virtually impossible. Thus, estimates were made using assumptions of normal force distributions at multiple body sites as appropriate. Ongoing and future evaluations will continue to investigate additional physical domains, including metabolic requirements, muscle power, and endurance/fatigue, when extending these analyses to the other ACFT tasks.

Summary

In summary, despite the known limitations, this preliminary report found that the 60-point minimum performance requirements for the ACFT deadlift are typically a reasonable match to several expected soldier tasks. However, while the three-repetition maximum deadlift requirement to lift 63.6 kg (140 lbs) may seem high to some, it was not always sufficient to ensure that soldiers can execute the absolute workload demands of several CSTs, such as casualty extraction for either men or women. Finally, the overall workloads of the CSTs evaluated were similar between men and women, from a physical perspective, i.e., peak torques at several major joints (knee, hip, lower back, elbow, shoulder), suggesting men and women perform CSTs and the ACFT deadlift events in largely similar ways despite differences in typical strength and anthropometry.

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