Applied Ergonomics 56 (2016) 27–33

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Quantifying warfighter performance in a target acquisition and aiming task using wireless inertial sensors

Steven P. Davidson [a, *], Stephen M. Cain [a], Ryan S. McGinnis [c], Rachel R. Vitali [a], Noel C. Perkins [a], Scott G. McLean [b]

[a] College of Engineering, University of Michigan, 2350 Hayward St, Ann Arbor, MI 48109, USA
[b] School of Kinesiology, University of Michigan, 401 Washtenaw Avenue, Ann Arbor, MI 48109, USA
[c] MC10 Inc., 9 Camp Street, Cambridge, MA 02140, USA

ARTICLE INFO

Article history:
Received 16 June 2015
Received in revised form 26 February 2016
Accepted 4 March 2016
Available online 25 March 2016

Keywords:
Aiming performance
Warfighter performance
Inertial measurement units
Fatigue

ABSTRACT

An array of inertial measurement units (IMUS) was experimentally employed to analyze warfighter performance on a target acquisition task pre/post fatigue. Eleven participants (5M/6F) repeated an exercise circuit carrying 20 kg of equipment until fatigued. IMUs secured to the sacrum, sternum, and a rifle quantified peak angular velocity magnitude (PAVM) and turn time (TT) on a target acquisition task (three aiming events with two 180° turns) within the exercise circuit. Turning performance of two turns was evaluated pre/post fatigue. Turning performance decreased with fatigue. PAVMs decreased during both turns for the sternum ($p < 0.001$), sacrum ($p = 0.007$) and rifle ($p = 0.002$). TT increased for the sternum ($p = 0.001$), sacrum ($p = 0.003$), and rifle ($p = 0.02$) during turn 1, and for the rifle ($p = 0.04$) during turn 2. IMUs detected and quantified changes in warfighter aiming performance after fatigue. Similar methodologies can be applied to many movement tasks, including quantifying movement performance for load, fatigue, and equipment conditions.

1. Introduction

1.1. Background

In a combat scenario, the performance of a warfighter is paramount to the safety and success of a mission. To promote this success, the modern warfighter is outfitted with the most advanced weapons, armor and technology. However, the benefits of modern technology often come at the cost of added weight. In combat, a warfighter is expected to carry over 20 kg of advanced armor (Birrell et al., 2007; O'Neal et al., 2014), weapons, ammunition, and support gear, while simultaneously maneuvering through a complex and often random environment. These additional load constraints may restrict or alter key movements, increase fatigue rate, and degrade warfighter performance (Birrell et al., 2007; Birrell and Haslam, 2009; Knapik et al., 1990a; O'Neal et al., 2014; Pandorf et al., 2002; Treloar and Billing, 2011).

Key components of warfighter performance are the ability to aim a rifle and to successfully acquire and hit a target. Overall aiming performance rests on the ability to react, identify, and stabilize on a target before accurate shot execution. It is understandably a challenge to quantify overall aiming performance given the random (real) environments that a warfighter negotiates and the small time window in which a warfighter can safely acquire a target and execute an accurate shot. Traditionally, studies evaluate the effects of load and fatigue on warfighter shooting performance by relying on a constrained, albeit easily interpretable, live fire shot accuracy outcome measure (Frykman et al., 2012; Knapik et al., 1990b; Swain et al., 2011). While the results of these studies show a decline in rifle marksmanship after strenuous anaerobic activity (Swain et al., 2011) and activity under load (Frykman et al., 2012), accuracy alone does not reveal the critical rifle movements prior to a trigger pull that are necessary when executing an accurate shot.

1.2. Objective

A promising means to detect and quantify the critical movements that establish shot accuracy is summarized herein by employing an array of miniature body-worn and rifle-mounted

* Corresponding author.
E-mail address: stevepd@umich.edu (S.P. Davidson).

http://dx.doi.org/10.1016/j.apergo.2016.03.001
0003-6870/

wireless inertial measurement units (IMUs). IMUs are inertial sensors that contain tri-axial angular rate gyroscopes and accelerometers, which can quantify three-dimensional (3D) segmental kinematics. IMU's, including body-worn IMU arrays, have been used to measure human movement in naturalistic environments, including those relevant to warfighters, athletes and workers (Cain et al., 2015; McGinnis et al., 2015a, 2015b; Soangra and Lockhart, 2012; Whiteside et al., 2014, 2015; Yang and Li, 2012). By outfitting warfighters with strategically placed IMUs, the critical turning movements of a warfighter's rifle and body (torso and pelvis) can be tracked and analyzed to reveal how the warfighter maneuvers to acquire a target.

This study employed this new experimental method (an IMU array) to identify and examine explicit warfighter aiming performance metrics pre and post fatigue in a simulated target acquisition task. The task involved repeatedly aiming a rifle while turning, completed in series with additional fatigue-inducing tasks. The experimental conditions included the effects of ammo and armor weight distribution that accelerate fatigue. We identified key biomechanical metrics of aiming performance using data resolved from the array of IMUs. These metrics were measured in both a rested state and a fatigued state, with the expectation that significant changes (i.e. decreased performance) would arise with fatigue.

2. Methods

2.1. Participant demographics

Eleven participants (5M/6F, 20.5 ± 1.6yrs, 1.75 ± 0.07 m, 70.97 ± 7.77 kg) were recruited from collegiate populations of reserve officers training core (ROTC) and club sport programs. The study goals and methods were approved by the University of Michigan Institutional Review Board and participants signed informed consent forms prior to participation.

2.2. Sensors and equipment

Participants were fitted for a military issue outer tactical vest (IOTV-III, Fig. 1C,D) with mock-ballistic plates and a mock-tactical assault panel (TAP, Fig. 1C,D) attached to the IOTV-III anteriorly (Fig. 1C). An M4 training rifle (Fig. 1A,C) with an attached red/green laser aiming device (NcSTAR Inc. City of Industry, CA) provided visual confirmation of target acquisition during the target acquisition task. Participants were also outfitted with a chest-worn wireless heart rate (HR) monitor (Polar RS400, Polar USA, Lake Success, NY) and three inertial measurement units (3-Space Sensor, Yost Engineering, Portsmouth, OH). The IMUs were attached to the participants' sternum, sacrum, and rifle to allow simultaneous measurement of both body and rifle movements (Fig. 1A–C). The IMUs were fixed to the rifle and sternum (outer IOTV-III) using zipties (Fig. 1A), and to the sacrum using a custom waist strap (Fig. 1B). Each IMU node included a MEMS accelerometer (3-axis) and angular rate gyroscope (3-axis) measuring accelerations up to 12 g, with 14-bit resolution, and a 650 $\mu g/\sqrt{Hz}$ noise floor and angular rates up to 2000 °/s, with 16-bit resolution, and a 0.03 $°/s/\sqrt{Hz}$ noise floor. Data were sampled at approximately 300 Hz, written to on-board flash memory, and subsequently downloaded to a computer via USB immediately after each testing session.

2.3. Experimental design and protocol

Participants performed an exercise circuit designed to simulate a military obstacle course and induce neuromuscular fatigue (McGinnis et al., 2015a). The circuit consisted of four obstacles completed in the following order (Fig. 2): 1) four maximum effort vertical jumps performed using a VERTEC vertical jump measurement stand (Vertec, Jump USA, Sunnyvale, CA), 2) three target acquisition tasks (three aiming events with two 180° turns in between), 3) twenty box step-ups (0.5 m high, ten steps per leg), and 4) five sprints with get-up and get-down tasks (five 10 m sprints with two standing to prone to standing transitions between each sprint). Rated perceived exertion (RPE), via the Borg CR10 scale (Borg, 2001), and HR were recorded between each obstacle in the circuit. Participants were familiarized with the obstacles, and performed a baseline trial run of the entire circuit before any load was added. Ballistic plates, IOTV-III, and TAP (~20 kg, Fig. 1C,D) were worn by the participants who then performed multiple rounds of the circuit until fatigue was reached. Fatigue was identified when a participant failed to reach a vertical jump height of 70% of his/her maximum non-fatigued, weighted vertical jump height (McGinnis et al., 2015a; Rodacki et al., 2002), or the point at which the participant reported a maximum RPE indicating that he/she could no longer safely perform the obstacles in the circuit.

2.3.1. Target acquisition task

The target acquisition task was created using two targets (6.3 cm black circles on white sheets of paper) spaced 12 m apart and 0.9 m high. At the beginning of the target acquisition task, the participants were verbally commanded to pick up the rifle and stabilize the laser within the black circle of target A (Fig. 3A). Once stabilized, the participants were instructed to perform a 180° turn and stabilize the laser within the black circle of target B (Fig. 3A). The participants performed a final 180° turn, again stabilizing the laser in the circle of target A (Fig. 3A). The participants then advanced in the aforementioned fatiguing circuit (~5 min) before repeating the next target acquisition task.

2.4. Data analysis

The acceleration and angular velocity sampled on the participant's torso (sternum), pelvis (sacrum), and rifle were measured by the attached IMUs Data from the three IMUs were downloaded, time-synchronized (using angular velocity magnitudes from each IMU during whole-body oscillations obtained by spinning/oscillating the participant in a swivel office chair), and parsed into the four individual obstacles using a custom MATLAB algorithm (The Mathworks, Inc., Natick, MA). The time periods for each target acquisition task (one per circuit) were identified and the acceleration and angular velocity data from each IMU were transformed from an IMU fixed frame into a lab fixed frame (x,y,z, Fig. 3B) using the method presented by McGinnis and Perkins, 2012.

2.4.1. Turn identification

During the target acquisition task, the two distinct 180° turns were identified for subsequent analysis that included the computation of the rifle heading angle (Fig. 3B). The rifle heading angle, defined as the angle in the horizontal plane between the rifle barrel and the y-axis (Fig. 3B), was computed after first identifying the 3Dorientation of the rifle in space. The 3D orientation followed from fusing the acceleration and angular velocity data using a complementary filter (McGinnis et al., 2014). The rifle heading angle was used to identify the beginning and end of each turn. Angles lying in the horizontal plane and describing the heading direction of the sternum and sacrum were similarly defined and computed.

Turn parameters were calculated individually for each of the sternum, sacrum, and rifle IMUs. Using the heading angle of each IMU, turns were defined when the heading angle for each IMU was within ±5° of 0° and 180° for the first turn and between 180° and

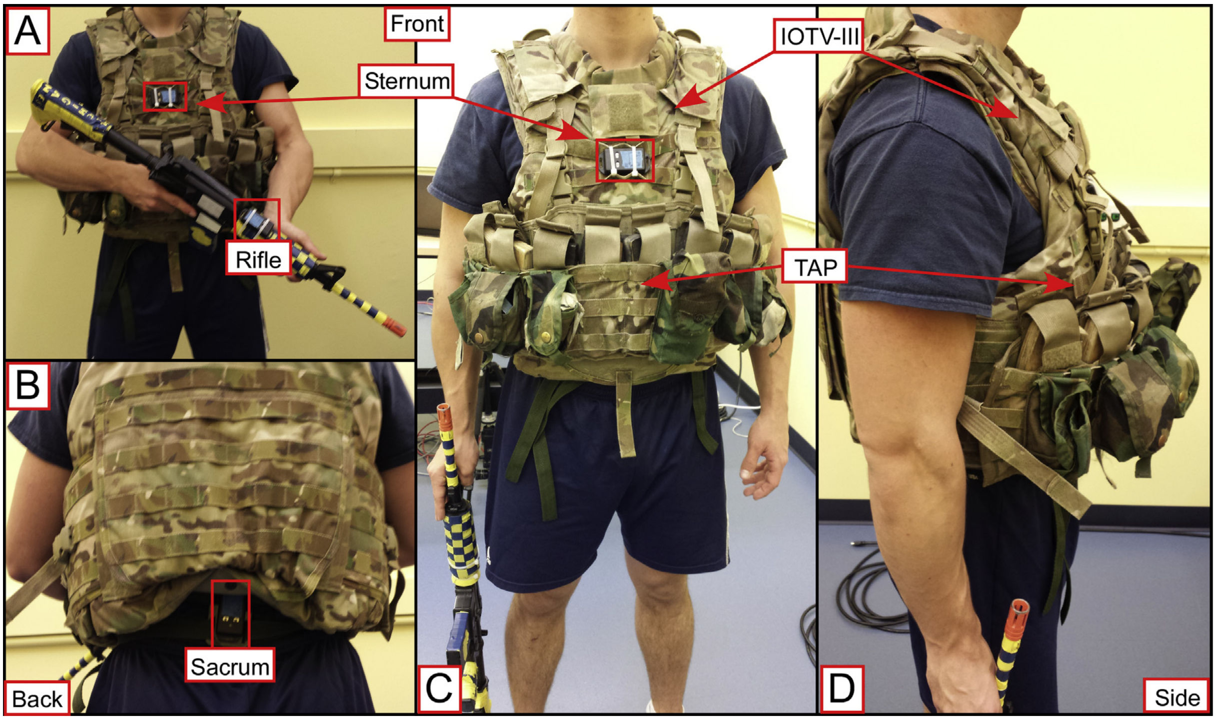

Fig. 1. Location of sternum (A, C), sacrum (B) and rifle (A) IMUs. Equipment that constitutes added load includes IOTV-III (C, D), TAP (C, D), and mock training rifle (A, C).

0°/360° (dependent on the turn direction) for the second turn (Fig. 3A). The angular velocity of each IMU within the turns was analyzed for the first (pre-fatigue) and the last (post-fatigue) loaded circuit.

2.4.2. *Statistical analysis*

For the turn portions of each target acquisition task, the peak angular velocity magnitude and the total turn time of the rifle, sacrum, and sternum IMUs were identified as biomechanical metrics that could potentially discriminate performance (Fig. 4). Comparisons of these metrics were made between the turns of the pre-fatigue and post-fatigue conditions. Paired t-tests were used to determine significant effects of fatigue ($\alpha = 0.05$). Corrections for multiple comparisons were not performed. The goal of this research was to identify useful rifle aiming performance metrics and to test the efficacy of the IMU array as a viable measurement tool, therefore a conservative α-level adjustment was deemed unnecessary.

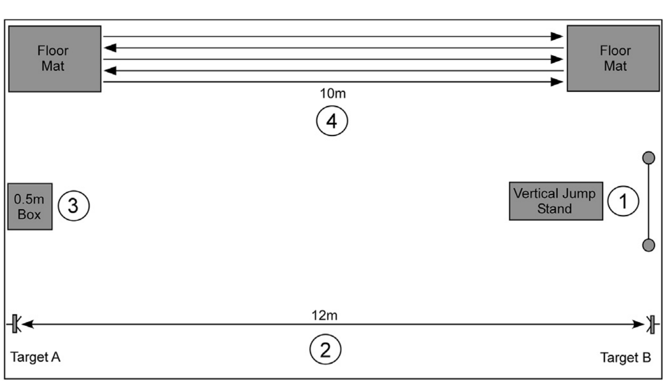

Fig. 2. Schematic diagram of the fatigue circuit consisting of the following obstacles: 1) Vertical jump, 2) Aiming task, 3) Box step-ups, 4) Sprint and get-up get-down run.

3. Results

Fig. 5 illustrates the changes between conditions (post-fatigue minus pre-fatigue) in peak angular velocity and turn time for the first turn. Separate results are reported for each participant and for the rifle, sacrum and sternum mounted IMUs. Fig. 6 contains the same results for the second turn. Participants underwent an average of 4.5 loaded circuits before reaching a fatigued state.

3.1. *Results of turns 1 & 2*

Overall, the peak angular velocity magnitude decreased significantly after fatigue for turn 1 by an average across all participants of 64.9 °/s ($p < 0.001$), 55.0 °/s ($p = 0.007$), and 80.8 °/s ($p = 0.002$), for the sternum, sacrum, and rifle IMUs, respectively (Fig. 5A). Similarly, the peak angular velocity magnitude decreased significantly after fatigue for turn 2 for the sternum, sacrum and rifle IMUs by an average across all participants of 56.5 °/s ($p < 0.001$), 50.5 °/s ($p < 0.001$), and 53.5 °/s ($p = 0.002$), respectively (Fig. 6A).

The turn time for turn 1 increased significantly after fatigue for the sternum, sacrum, and rifle IMUs, by an average across all participants of 0.37 s ($p = 0.001$), 0.47 s ($p = 0.003$), and 0.26 s ($p = 0.02$), respectively (Fig. 5B). However, the turn time for turn 2 increased significantly after fatigue only for the rifle IMU by an average of 0.14 s ($p = 0.04$) across all participants (Fig. 6B).

3.2. *Comparison between fatigued turns 1 & 2*

Fig. 7 reports the differences in peak angular velocity and turn time between the two turns of the fatigued state for each participant (turn 2 minus turn 1). When comparing the two turns, the peak angular velocity magnitudes for the sternum and sacrum IMUs in turn 1 were significantly smaller than those for turn 2 by an average of 21.1 °/s ($p = 0.02$) and 21.0 °/s ($p = 0.03$), respectively (Fig. 7A). Similarly, turn 1 had significantly longer turn times for the

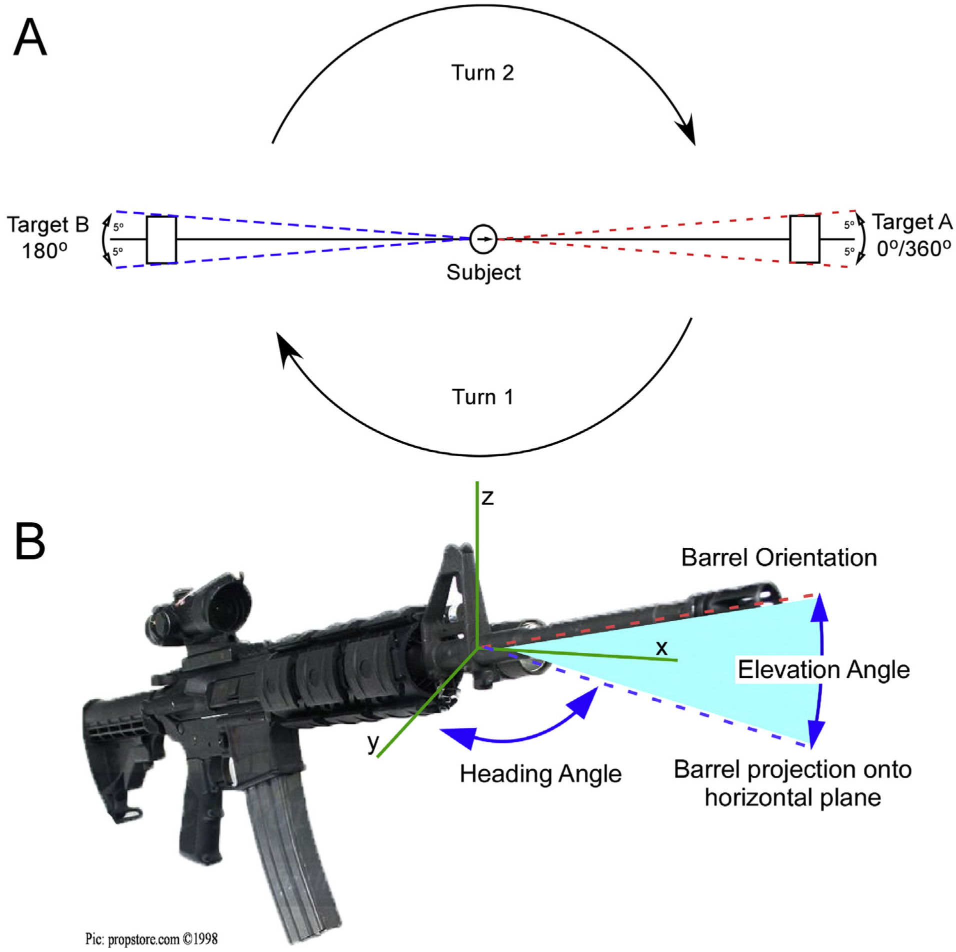

Fig. 3. A) Schematic diagram of the target acquisition task. B) Definition of rifle heading angle relative to lab-fixed frame.

sternum, sacrum, and rifle IMUs; taking an average of 0.26 s ($p = 0.02$), 0.35 s ($p = 0.03$), and 0.19 s ($p = 0.003$) longer than turn 2, respectively (Fig. 7B).

3.3. Comparison of pre/post-fatigue HR

Relative to the HR measured in the remainder of the circuits, HR measured in the final (fatigue) circuit dropped significantly during the target acquisition task. On average, participant HR fell 4.72 bpm ($p < 0.001$) from the beginning of the target acquisition task. Pre-fatigue HR did not show any significant changes during the target acquisition task.

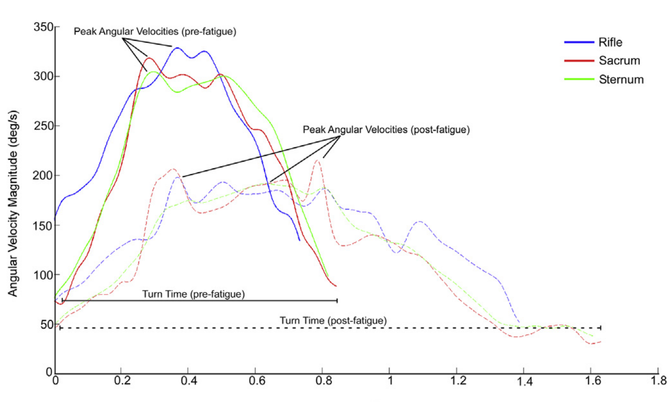

Fig. 4. Example angular velocity data from turn 1 of a representative trial. Solid lines represent pre-fatigue angular velocity magnitude of the rifle, sacrum, and sternum IMUs. Dashed lines represent analogous quantities post-fatigue. The peak angular velocity magnitudes and the turn times are labeled.

4. Discussion

The results above confirm the ability of IMUs to measure movement and detect performance changes in an unconstrained environment. Discrete changes in both peak angular velocity magnitude and turn time quantify decreased performance in maneuvering and acquiring a target after the onset of fatigue. In addition to detecting these changes in performance, more subtle performance changes are also observable between the two turns of the fatigued state. A comparison of the turns (Fig. 7) reveals that performance in turn 1 is significantly lower than that of turn 2 for all measures except rifle peak angular velocity magnitude. It is reasonable to assume that these increases in performance derive from the onset of fatigue recovery. Frykman et al., 2012 and Ito et al., 2000 both show that full fatigue recovery during a shooting task occurs within minutes (Frykman et al., 2012) and within 90 s in some cases (Ito et al., 2000). While the present target acquisition task is too short (15 s–20 s) to allow full fatigue recovery, the IMUs detect small increases in performance that indicate the beginning of fatigue recovery. Further evidence supporting fatigue recovery is observed in the significant HR decrease of 4.72 bpm measured

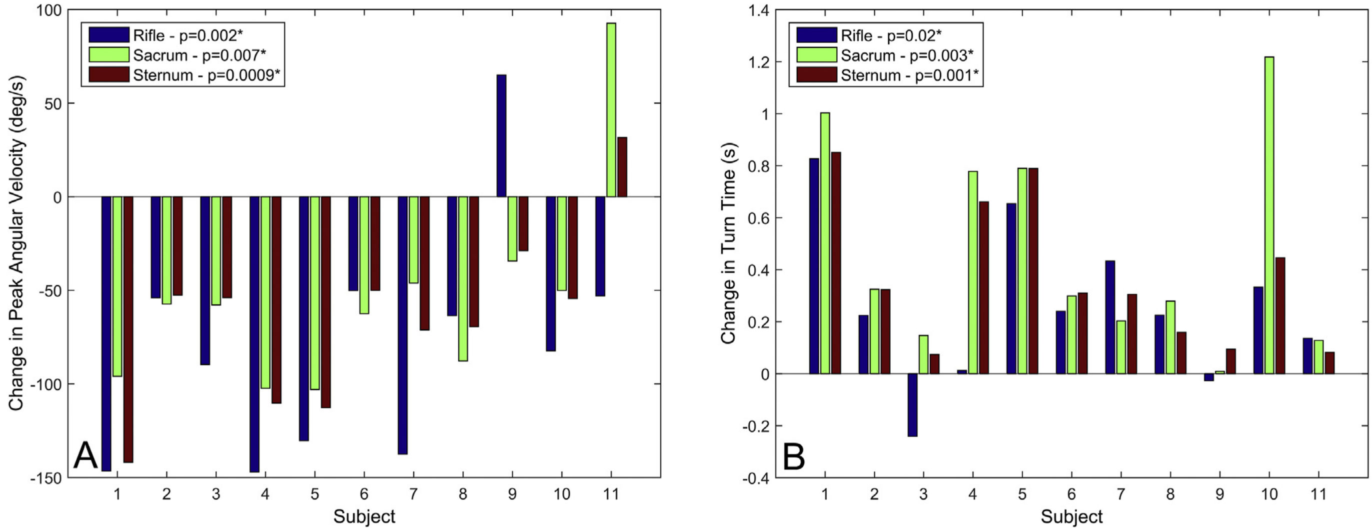

Fig. 5. Change in peak angular velocity (A) and change in turn time (B) from pre- to post-fatigue for turn 1. Results are shown for the rifle, sacrum and sternum mounted IMUs for each of the eleven participants.

across the target acquisition task. This drop approaches the significance threshold of ±5 bpm outlined by Zhang et al., 2008.

Data from IMU quantify differences in aiming performance due to fatigue that would otherwise remain undetected by visual observation alone. In particular, data from the IMU array tracks how a warfighter maneuvers his/her body and rifle to acquire a new target originally outside of the field of view. This maneuver first utilizes gross motor movements of the body to execute a turn transitioning to fine motor skills to effectively acquire a target (Era et al., 1996; Zatsiorsky and Aktov, 1990). Commonly, only the latter is used to assess aiming accuracy often in the context of a simple stationary aiming task (Knapik et al., 1990a, 1996; Zatsiorsky and Aktov, 1990). While final aiming accuracy is important, the movements that precede a trigger pull are critical for establishing the conditions for aiming success. Thus, quantifying both gross and fine motor movements is important in evaluating overall rifle aiming performance and the effects of load and fatigue on performance. Evaluating gross and fine motor skills in tandem provides a more comprehensive characterization of warfighter aiming performance than can be revealed in stationary aiming tasks alone. The reduction in performance with fatigue manifests in changes in multiple factors (e.g., angular velocity and turn time) that are readily measured using the IMU array.

The technology and methods presented herein may promote new performance measures and training programs. Quantifying how target acquisition movements are affected by fatigue, weight configuration, or terrain might improve training programs and equipment design including the design for load carriage. Moreover, detecting changes in warfighter movement at varying levels of fatigue, load, and equipment conditions (in the current study, the IOTV-III design and the load configuration remained constant) might indicate the combat readiness of warfighters during combat simulations. However, it is possible that performance degradations from fatigue will be magnified if additional weight and/or off-center mass distributions are introduced (Pandorf et al., 2002).

Accurately quantifying fatigue is difficult due to the lack of an

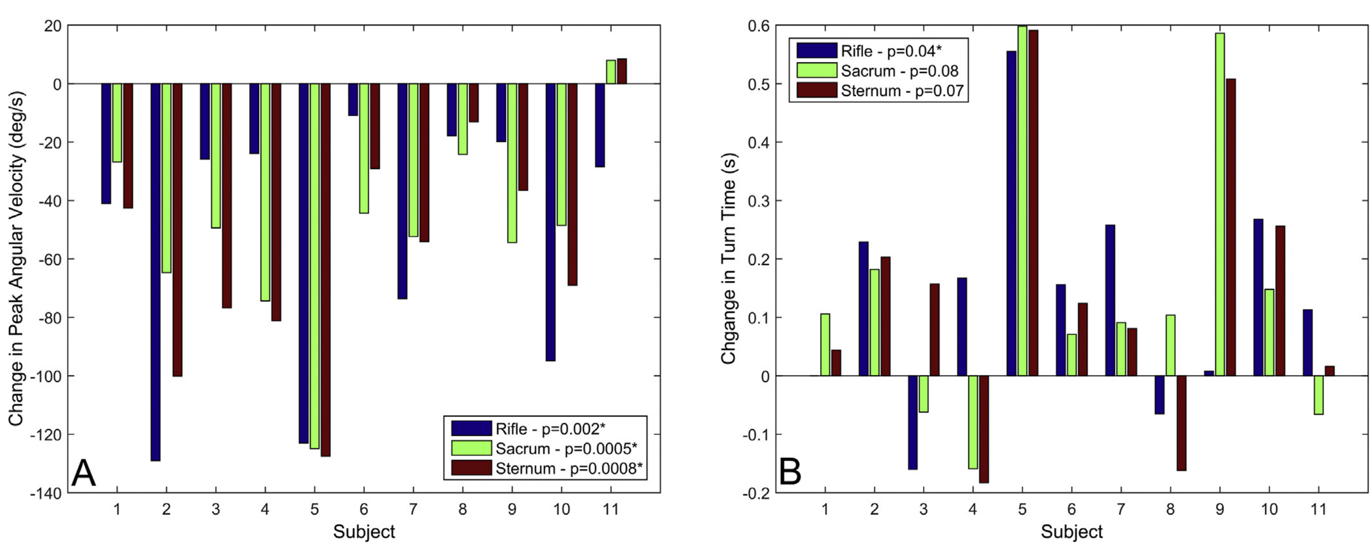

Fig. 6. Change in peak angular velocity (A) and change in turn time (B) from pre- to post-fatigue for turn 2. Results are shown for the rifle, sacrum and sternum mounted IMUs for each of the eleven participants.

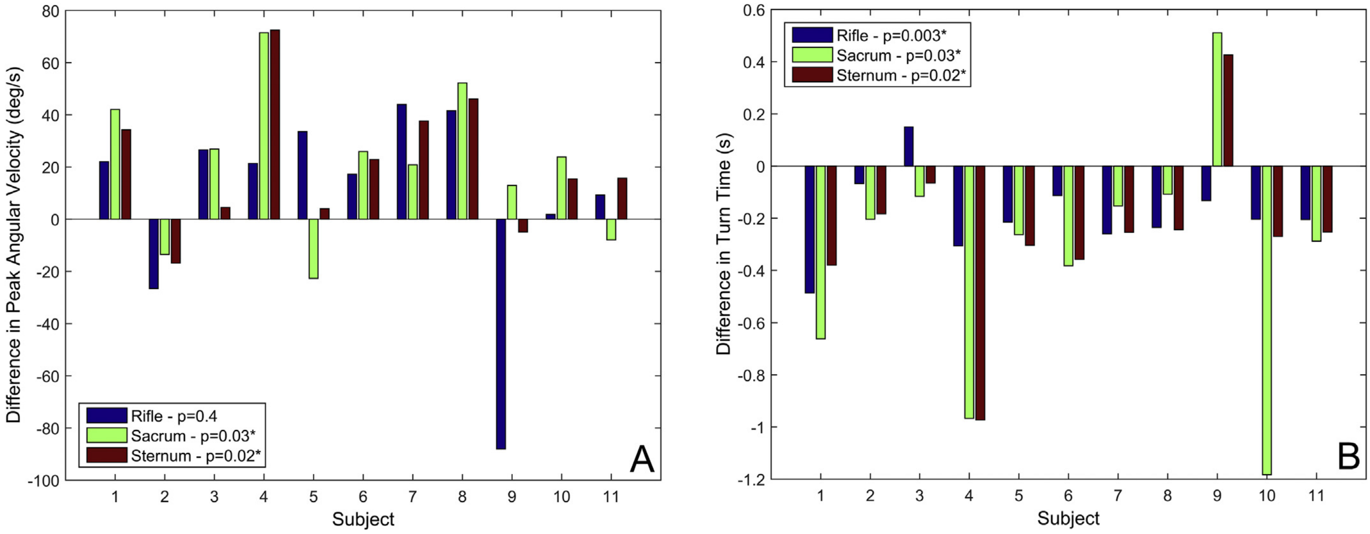

Fig. 7. Difference (turn 2 minus turn 1) between the two turns of the fatigued state for (A) peak angular velocity magnitudes and (B) turn time.

accurate fatigue detection method and potentially large differences in the fatigue resistance and mental drive of individual participants. To reduce this effect, two separate methods of identifying fatigue were used: the Borg CR10 scale (Borg, 2001) and a vertical jump reduction threshold (70% of pre-fatigue maximum; Rodacki et al., 2002). This combination of fatigue detection methods has been previously used (McGinnis et al., 2015a), and diminishes, but does not remove, any remaining differences due to participant motivation, mental determination, fitness, and ability.

Due to the safety concerns, neither live fire nor simulated fire tests could be performed at our facility, thus preventing the quantification of two important rifle aiming measurements: shooting accuracy and trigger pull. The latter is important because, despite the short duration of the trigger pull, the resulting disturbance can heavily influence shooting performance, with the potential to diminish shooting accuracy (Chung et al., 2011). Nevertheless, the IMU array and the methods outlined herein could be readily deployed in facilities that allow live fire or simulated fire testing.

While the results herein focus on turning motions prior to aiming, the methods readily extend to quantifying additional motions relevant to any aiming task. The IMU data can provide a wealth of information describing the simultaneous kinematics of both the human participant (e.g., the kinematics of torso and sternum among other body segments) and the rifle (e.g., the instantaneous rifle elevation and heading angles in Fig. 3B) that characterize rifle aiming motions. Such information may reveal additional rifle aiming factors, including, for example, aiming techniques, reaction times, discrete adjustments prior to trigger pull (Zatsiorsky and Aktov, 1990) and unintended rifle movements due to breathing (Chung et al., 2006).

The methods used in this study translate to studies and applications well beyond rifle aiming and military use. IMUs have already shown utility in quantifying human performance (Cain et al., 2015; McGinnis et al., 2015a, 2015b; Soangra and Lockhart, 2012; Whiteside et al., 2014, 2015; Yang and Li, 2012), and will likely find pervasive use due to their non-invasive tracking of body segmental kinematics in any environment. As illustrated in this paper, IMUs are particularly well suited for pre/post comparisons of performance under load (e.g. fire fighter O_2 tanks, law enforcement body armor), fatigue (e.g. high performance athletics, repetitive movement in industry), and equipment restrictions (e.g. harnesses, helmets, sports pads), but also have potential to detect more discrete movements such as tracking rehabilitation progress, identifying postural and gait deformities, and even analyzing lifting or athletic technique.

5. Conclusion

A body-worn and rifle-mounted array of miniature IMUs yields a novel method to identify rifle aiming performance and the effects of fatigue. Traditional metrics of aiming performance, such as shooting accuracy, measure only one part of the complex motions that warfighters use to identify, acquire and neutralize threats in the field. The results reveal significant degradation of performance with fatigue in an example dynamic aiming task. The results also highlight the ability of IMUs to accurately quantify key timing metrics while simultaneously quantifying the associated movements of the human participant and rifle. The technology and methods herein may also quantify the full range of body movements that warfighters exhibit while aiming in complex environments including outdoor obstacle courses with or without live fire exercises. Looking forward, the same methodology can extend to many applications involving pre/post comparisons of performance due to fatigue, load, and equipment variation.

Acknowledgments

Funding was provided by the U.S. Army Natick Soldier Research, Development, and Engineering Center. Project: IMU array technology and algorithms for field-based warfighter performance assessment Grant#: W911QY-13-C-0011.

References

Birrell, S.A., Hooper, R.H., Haslam, R.A., 2007. The effect of military load carriage on ground reaction forces. Gait Posture 26 (4), 611–614. http://dx.doi.org/10.1016/j.gaitpost.2006.12.008.

Birrell, S.A., Haslam, R.A., 2009. The effect of military load carriage on 3-D lower limb kinematics and spatiotemporal parameters. Ergonomics 52 (10), 1298–1304. http://dx.doi.org/10.1080/00140130903003115.

Borg, G., 2001. Rating scales for perceived physical effort and exertion. In: Karwowski, W. (Ed.), International Encyclopedia of Ergonomics and Human Factors, vol. 3. Taylor and Francis, London and New York, pp. 538–541.

Cain, S.M., McGinnis, R.S., Davidson, S.P., Vitali, R.V., Perkins, N.C., McLean, S.G., 2015. Quantifying performance and effects of load carriage during a challenging balancing task using an array of wireless inertial sensors. Gait Posture. http://

dx.doi.org/10.1016/j.gaitpost.2015.10.022.

Chung, G.K.W.K., Nagashima, S.O., Delacruz, G.C., Lee, J.J., Wainess, R., Baker, E.L., 2011. Review of Rifle Marksmanship Training Research. Cresst Report 783. University of California, Los Angeles. Available at: http://calhoun.nps.edu/handle/10945/37927 (accessed 22.05.15.).

Chung, G.K.W.K., Delacruz, G.C., de Vries, L.F., Bewley, W.L., Baker, E.L., 2006. New directions in rifle marksmanship research. Mil. Psychol. 18 (2), 18. Available at: serialssolutions.com/?sid=google&auinit=GKWK&aulast=Chung&atitle=New+directions+in+rifle+marksmanship+research&id=doi:10.1207/s15327876mp1802_5 (accessed 22.05.15.).

Era, P., Konttinen, N., Mehto, P., Saarela, P., Lyytinen, H., 1996. Postural stability and skilled performance–a study on top-level and naive rifle shooters. J. Biomech. 29 (3), 301–306.

Frykman, P.N., Merullo, D.J., Banderet, L.E., Gregorczyk, K., Hasselquist, L., 2012. Marksmanship deficits caused by an exhaustive whole-body lifting task with and without torso-borne loads. J. Strength Cond. Res. 26 (Suppl. 2), S30–S36.

Ito, M.A., Sharp, M.A., Johnson, R.F., Merullo, D.J., Mello, R.P., 2000. Rifle shooting accuracy during recovery from fatiguing exercise. In: 22nd Army Science Conference. Baltimore, MD. Available at: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA414374 (accessed 22.05.14.).

Knapik, J., Staab, J., Bahrke, M., Reynolds, K., Vogel, J., O'Connor, J., 1990a. Soldier Performance and Mood States Following a Strenuous Road March. Manuscript Report. Army Research Inst. of Environmental Medicine, Natick, MA. Available at: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA217895 (accessed 22.05.15.).

Knapik, J., Daniels, W., Murphy, M., Fitzgerald, P., Drews, F., Vogel, J., 1990b. Physiological factors in infantry operations. Eur. J. Appl. Physiol. Occup. Physiol. 60 (3), 233–238.

Knapik, J., Harman, E., Reynolds, K., 1996. Load carriage using packs: a review of physiological, biomechanical and medical aspects. Appl. Ergon. 27 (3), 207–216. Available at: http://www.sciencedirect.com/science/article/pii/0003687096000130 (accessed 22.05.15.).

McGinnis, R.S., Perkins, N.C., 2012. A highly miniaturized, wireless inertial measurement unit for characterizing the dynamics of pitched baseballs and softballs. Sensors 12 (9), 13. Available at: http://www.mdpi.com/1424-8220/12/9/11933/htm (accessed 22.05.15.).

McGinnis, R.S., Cain, S.M., Davidson, S.P., Vitali, R.V., McLean, S.G., Perkins, N.C., 2014. Validation of complimentary filter based IMU data fusion for tracking torso angle and rifle orientation. In: American Society of Mechanical Engineers International Mechanical Engineering Congress and Symposium. Montreal, Canada. Available at: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleID=2204669 (accessed 22.05.15.).

McGinnis, R.S., Cain, S.M., Davidson, S.P., Vitali, R.V., Perkins, N.C., McLean, S.G., 2015a. Quantifying the effects of load carriage and fatigue under load on sacral kinematics during countermovement vertical jump with IMU-based method. Sports Eng. http://dx.doi.org/10.1007/s12283-015-0185-3.

McGinnis, R.S., Cain, S.M., Davidson, S.P., Vitali, R.V., McLean, S.G., Perkins, N.C., 2015b. Inertial sensor and cluster analysis for discriminating agility run technique, 9th IFAC Symposium on Biological and Medical Systems. Berlin, GER., 48 (20), 423–428. http://dx.doi.org/10.1016/j.ifacol.2015.10.177.

O'Neal, E.K., Hornsby, J.H., Kelleran, K.J., 2014. High-intensity tasks with external load in military applications: a review. Mil. Med. 179 (9), 950–954. http://dx.doi.org/10.7205/MILMED-D-14-00079.

Pandorf, C.E., Harman, E.A., Frykman, P.N., Patton, J.F., Mello, R.P., Nindl, B.C., 2002. Correlates of load carriage and obstacle course performance among women. Work 18 (2), 179–189. http://dx.doi.org/10.1080/00140130903003115.

Rodacki, A.L., Fowler, N.E., Bennett, S.J., 2002. Vertical jump coordination: fatigue effects. Med. Sci. Sports. Exerc. 34 (1), 105–116.

Soangra, R., Lockhart, T.E., 2012. A comparative study for performance evaluation of sit-to-stand task with body worn sensor and existing laboratory methods. Biomed. Sci. Instrum. 48, 407–414.

Swain, D.P., Ringleb, S.I., Naik, D.N., Butowicz, C.M., 2011. Effect of training with and without a load on military fitness tests and marksmanship. J. Strength Cond. Res. 25 (7), 1857–1865.

Treloar, A.K., Billing, D.C., 2011. Effect of load carriage on performance of an explosive, anaerobic military task. Mil. Med. 176 (9), 1027–1031.

Whiteside, D., Deneweth, J.M., Pohorence, M.A., Sandoval, B., Russell, J.R., McLean, S.G., Zernicke, R.F., Goulet, G.C., 2014. Grading the functional movement screen: a comparison of manual (real-time) and objective methods. J. Strength Cond. Res. http://dx.doi.org/10.1519/JSC.0000000000000654.

Whiteside, D., Deneweth, J.M., Bedi, A., Zernicke, R.F., Goulet, G.C., 2015. Femoacetabular impingement in elite ice hockey goaltenders: etiological implications of on-ice hip mechanics. Am. J. Sports Med. 43 (7), 1689–1697. http://dx.doi.org/10.1177/0363546515578251.

Yang, S., Li, Q., 2012. Inertial sensor-based methods in walking speed estimation: a systematic review. Sensors 12, 6102–6116. http://dx.doi.org/10.3390/s120506102.

Zatsiorsky, V.M., Aktov, A.V., 1990. Biomechanics of highly precise movements: the aiming process in air rifle shooting. J. Biomech. 23 (Suppl. 1), 35–41.

Zhang, J., Fletcher, J.G., Harmsen, W.S., Araoz, P.A., Williamson, E.E., Primak, A.N., McCollough, C.H., 2008. Analysis of heart rate and heart rate variation during cardiac CT examinations. Acad. Radiol. 15 (1), 40–48. http://dx.doi.org/10.1016/j.acra.2007.07.023.