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Holistically assessing dismounted warfighter military performance: bridging science and operational relevancy

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Received 29 May 2024
Accepted 16 January 2025

Check for updates

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To cite: Sperlein J, Hinde K, Karakolis T, *et al*. *BMJ Mil Health* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/military-2024-002748

ABSTRACT
Dismounted warfighter physical and cognitive performance is complex, involving interdependent domains such as mobility, lethality, survivability and sustainability. This article provides an overview of topics presented during the 'holistically assessing dismounted infantry performance: bridging science and operational relevancy' session of the sixth International Congress on Soldiers' Physical Performance, held in London, UK, 2023. These topics include the investigation of multivariate aspects of dismounted performance at both the individual warfighter and squad levels. Discussion includes a general approach to quantifying warfighter and squad-level dismounted performance, specific body-worn sensors used to investigate performance, including heart rate variability and movement mechanics, a specific investigation into the effect of hearing acuity on individual and group performance, and lastly moving towards predicting performance with body-worn sensors.

INTRODUCTION
Dismounted warfighter operations are increasingly complex, with the warfighters' physical burden and cognitive demands remaining high.[1] Effective field-based evaluations challenge the intersection of scientific rigour (eg, resolution, data storage, etc) and field-based demands (eg, portability, battery, warfighter transparency, etc). Objectively measuring and quantifying metrics across multiple warfighting domains (eg, mobility, lethality and survivability), and the interactions between these metrics, likely provides a holistic analysis of overall warfighter mission performance. Moreover, applying this approach to multiple participants allows for squad-level metrics and outcomes. By characterising both warfighter and squad-level dismounted performance across multiple domains, a more comprehensive picture of dismounted performance and effectiveness is likely gained.

The purpose of this article is to provide a summary of six unique but related approaches and findings, bridging laboratory-based metrics with operational performance. These topics were presented in the 'Holistically assessing dismounted infantry performance: bridging science and operational relevancy' session of the sixth International Congress on Soldiers' Physical Performance, held in London, UK, 2023. The article starts with an approach towards holistically assessing a warfighter's dismounted performance and continues into initial findings from squad-based performance quantification. The next two topics focus on specific means to quantify dismounted activities. These include evaluating different wearable devices to quantify heart rate variability (HRV) in a field environment and movement mechanics using portable methods. Lastly, the implications of quantifying performance are described as related to hearing acuity and overall performance prediction.

For the purposes of this article, the authors aimed to summarise recent approaches and studies rather than establish common definitions for terms used, such as performance, mobility, lethality and survivability. While common definitions are valuable when sharing protocols, metrics, analyses and conclusions, consensus definitions remain a task for another article.

Holistically quantifying dismounted warfighter performance
Military scientists often investigate the impact of current and prototype body-borne and warfighter-carried kits such as rucksacks,[2] body armour,[3] exoskeletons[4] and small arms weapon systems.[5] Understanding the impact on warfighter mobility, lethality and survivability can inform the development of prototypes, such as military-specific exoskeletons,[4 5] as well as the trade space between similar items (eg, lightweight vs traditional body armour[4]). While there is no single 'right' approach to quantify the impact, a holistic and methodical assessment likely provides informative outcomes on the impact of dismounted performance.

The initial development of an assessment is often informed by basic questions, including defining mobility, lethality and even performance. These definitions may be guided by requirements or defined by consensus of test personnel and stakeholders. Once basic definitions are identified, the militarily relevant outcomes are needed to determine the critical outcomes to quantify. While single performance metrics (eg, time to complete a ruck march) may be adequate, often, broader mission effectiveness outcomes are of interest, which are likely a combination of outcomes such as overall completion times, responsiveness to target presentation, specific times needed to complete an aspect of a task, user acceptance or compatibility with the kit and future mission tasks. Additional analysis of relationships between outcomes (eg, time to complete relative to percentage of shots to a specific location

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on a target) may provide even more relevant information on the tradeoffs provided by the kit in question.

When developing the assessment test events and conditions, a baseline condition with the current kit provides a benchmark against which to assess the impact of new or emerging capabilities for relevant tasks. For example, if the item being considered is used during live-fire engagements, a comprehensive marksmanship task with authentic felt recoil and weapon cycling dynamics is likely more informative compared with simulated firing. This task might include magazine reloads and malfunctions, varied target distance and firing positions (standing, kneeling and prone), on the move, down- and across-range. Additional complexity could be added with decision-making such as shoot/don't shoot and variable hit(s)/location of hit(s) on targets.

Finally, while objective measures are often considered the 'best' measures, subjective or open-ended feedback may be valuable. Subjective measures allow participants to provide feedback on aspects that may not have been included or considered but are nonetheless highly valuable to either inform future assessments or development cycles.

Emerging results from the field: quantifying team combat performance in dismounted infantry squads

After-action reviews (AARs) allow squads to identify areas for improvement and observer controllers (OCs) to provide feedback with the goal of increasing performance. While observational feedback by OCs is essential, modern sensors (eg, inertial measurement units (IMUs), global positioning systems (GPS) and motion capture) provide an opportunity for quantitative metrics to bolster traditional AARs. Yet, interpretation and usage of that data are still hampered by a lack of understanding about what aspects of squad performance are meaningful to quantify.

To begin to resolve that issue, analyses must be tailored to specific battle drills to remove some of the battlefield's inherent complexities. Battle drills are standardised collective military actions made in response to common battlefield occurrences.[6] Unique metrics should be developed for each drill, although some metrics, like movement speeds or rates of fire, may be tracked in multiple drills. By focusing on battle drills, testers and evaluators can more readily ensure operational relevancy, task standardisation, repeatability and generalisability of findings.

Research focused on developing novel metrics of squad performance, measuring them with a suite of sensors and evaluating their relation to the overall quality of execution was undertaken by the US Army Combat Capabilities Development Command Soldier Centre in support of the Measuring and Advancing Soldier Tactical Readiness and Effectiveness Programme's Small Unit Performance Analytics.[7] Following institutional review board approval, data were collected from 36 squads using the following wearables and techniques:

a. Demographics, anthropometrics and baseline marksmanship ability.
b. Kinematics through IMUs and three-dimensional motion capture.
c. Position tracking via GPS.
d. Stress response through physiological status monitoring and blood/salivary biomarkers.
e. Squad mission outcomes via (a) observation and video analysis and (b) communication recordings.
f. Subjective military expert OC observation of the overall quality of battle drill execution.

Metrics derived from (1) to (5) were inputs to models to predict outcomes in (6) and quality of performance constructs, including communication, fire effectiveness and initiative/leadership. Model development focused on data collected from a squad attack, where 11 communication, fourmovement/positioning, three scanning, six firing rate/casualty and two physiological metrics were identified as strong predictors of squad performance. Integrating these metrics and predictive models into future AAR training tools would provide squads with quantitative assessments leading to more efficient and effective training, increasing the readiness and lethality of our warfighters.

Development of a framework to profile physiological, psychological and psychophysiological variables to predict dismounted warfighter performance

Dismounted warfighter operations are increasingly complex, with the warfighters' physical burden remaining high and their cognitive demands greatly increasing.[1] Commanders and researchers need to identify key indicators that predict individual and team performance to facilitate optimisation through targeted training and/or technology. To identify some of these key target indicators, a two-phase research project was completed using two scheduled field training exercises (FTX) conducted in the Welsh Black Mountains.

The data collection approach comprised a pre-FTX baseline, then pre-, during-, and end-FTX measures. Measurement devices and techniques were selected that collected or allowed for raw data extraction. Also, as the FTXs had a best-effort performance element, the approach needed minimally intrusive/burdensome measures for the warfighters and exercise directing staff.

Phase 1 used Exercise Cambrian Patrol, a 48-hour, 60 km patrolling event where eight-person patrols complete a succession of scored tasks assessing military skills and physical and mental endurance. Five patrols completed an extensive range of physiological, psychological, biochemical and psychophysiological measurements. Phase 1 provided the research team with information on the practicality and effectiveness (ie, did they work and did they show anything) of the data collection methods used, the variables measured and the data ingestion and analysis techniques utilised, allowing them to be down-selected for Phase 2.

Phase 2 used Exercise Long Reach, completed by British Army Officer Cadets, where patrols cover ~50 km, navigating 13 checkpoints within a 36-hour cut-off time. 59 officer cadets completed the down-selected Phase 1 measures, including an extended baseline duration (1 vs 5 days). Streamlined data handling processes allowed direct ingestion into an interrogable database for cleaning and analysis. Techniques used included exploratory machine learning analysis, where physical performance predictions were approached as a regression problem, while psychological performance predictions were approached as a classification problem. Phases 1 and 2 generated the following key recommendations:

a. Given their relatedness to the physical performance indicator measured, physical performance, sleepiness and/or sleep should be monitored prior to and during FTX.
b. Due to associations observed with changes in physical performance, future wearable devices to monitor and predict warfighter physical performance should quantify movement distance, duration and physical activity levels. Wearable devices should allow for raw data extraction to facilitate data analysis and modelling.
c. Due to the associations seen with cognitive performance, indicators of stress, anxiety and sleepiness and/or sleep should be monitored prior to and during FTX, and consideration

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should be given to training stress reactivity and enhancing sleep quality.

d. Given their support from the existing literature, future research predicting warfighter performance should continue to develop and include robust and field-deployable heart rate and HRV measurement approaches.
e. Future studies should build on this approach, focusing on live data ingestion to provide real-time actionable outcomes during data collection.
f. Future research should involve larger-scale studies and the implementation of continuous and integrated data capture to quantify 'predictor' and 'performance' variables. This could be achieved through bespoke military exercises, looped 'courses' and repeated data collections on regularly scheduled FTX.

Measuring the impact of hearing impairment and hearing protection devices on dismounted combat performance

The sense of hearing is heavily relied upon in dismounted combat operations. It is important for effective communication and the detection and identification of critical signals, localising sound sources and maintaining acoustic stealth. Unfortunately, hearing loss is prevalent in the armed forces due to hazardous noise exposure[8 9] and the often-inadequate usage of hearing protection.[10 11] Despite this, relatively few studies have explored the impact that hearing loss has on operational performance, particularly in field settings. This is partially due to methodological challenges in comparing trained operators with and without hearing impairment, but perhaps even more critically due to a lack of validated measures of operational performance in dismounted combat environments.

Understanding how hearing acuity impacts operational performance is essential to inform auditory fitness for duty criteria, define requirements for hearing protection devices and justify the use of engineering controls to limit noise in operational environments. To address this knowledge gap, researchers from the Audiology and Speech Pathology Centre at Walter Reed National Military Medical Centre and their Department of Defence collaborators executed a series of studies that each follow the same general methodological approach. Experienced service members with relatively normal hearing are recruited to conduct combat training exercises while their hearing is systematically degraded using helmet-mounted hearing loss simulation systems or hearing protection devices, and their performance is measured. The initial studies used simple paintball-based combat scenarios focused at the individual level[12] but have expanded over time to the fire-team level, incorporating actual weapons firing blanks and relying on a variety of metrics to assess performance in more complex combat exercises. These metrics include Multiple Integrated Laser Engagement System data to identify who shot whom and when, GPS data to capture movement, audio recordings to assess verbal communication, GoPro video recordings to provide a point-of-view perspective, as well as subjective feedback from observers and participants.[13] Overall, these studies have shown that hearing impairment can have a significant impact on lethality, survivability and mission success. However, improvements to the methodology are still needed to better understand the myriad ways that hearing acuity might affect performance at the squad level in valid combat scenarios that follow standard infantry doctrine.

Achieving a delicate balance between scientific rigour, ecological validity and logistical constraints inherent in operational settings presents a formidable hurdle. Thankfully, the endeavour to establish specific measurement protocols and performance metrics for objectively quantifying operational performance in small units has gained momentum.[7] By aligning our studies with these methodologies, we hope to provide impactful data regarding the effects that hearing impairment and/or hearing protection have on dismounted combat performance.

Wearing your heart on your sleeve (or wrist): wearable technologies for HRV in the military – an update

HRV can be useful in understanding the cardiovascular response to stress. Generally, high HRV reflects the ability of the autonomic nervous system to adapt to stressors, while low HRV can, but not always, be indicative of fatigue,[14] overtraining[15–17] or health issues.[18–20] HRV should always be viewed in the context of relative changes with respect to an individual's baseline. HRV, as a single outcome, is unlikely to be useful by itself as it can be confounded by both fixed and acutely changeable factors and does not correlate to some physiological readiness indicators (eg, muscle soreness).[21] Integrating subjective measures and other physiological parameters alongside HRV will likely have better utility for evaluating adaptation[21] and understanding complex occupational scenarios.[22]

Traditional clinical measures of HRV are expensive and impractical for field monitoring. While previous work[23] evaluated wearable devices for HRV, the paper focused on 24-hour measurements. Shorter measurements (overnight or upon waking) are becoming increasingly popular for monitoring purposes due to reduced participant burden and the development of new technology. As such, an update to a previously published literature review[23] was provided. Technology searches were conducted to identify wearable devices that measure HRV. Information from firsthand experience of using the devices and supporting scientific literature was examined to explore accuracy and usability.

Single-lead ECGs/patches enable longitudinal measurements and are generally the most accurate wearable devices for HRV, are medical grade and are commonly used as reference standards.[24 25] However, it is unknown if they comfortably integrate with protective military equipment, and many patches are single use (ie, negative environmental impact). Clothing garments with low-profile built-in sensors offer additional physiological parameters; however, a good fit is required to avoid excessive artefacts during vigorous movement.[26] Chest straps offer a simple, durable alternative and excellent validity when compared with the gold standard,[27] yet they provide no direct access to data and have limited acceptance for overnight monitoring. Smartwatches/straps are an accepted form factor; however, many lack external validation for HRV or demonstrate poor validity (eg, Bellenger *et al*[28]). Many watches display HRV as an arbitrary rating rather than actual HRV measures and/or due to proprietary algorithms, make access to raw data difficult for research. Alternatively, smart rings are easy to wear and address measurement noise due to less movement at the finger versus the wrist. However, they currently only provide one HRV parameter, which may not be suitable for research purposes.

The trade-off between accuracy and practicality is important when down-selecting devices. Despite a device having the ability to obtain high-quality data, if uncomfortable to wear, unable to withstand rugged environments or has a high user burden, the likely result will be low data quantity with subsequent limited use. Other considerations include data accessibility (ie, security and data ownership), battery life, internal memory and timing of measurement.

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The implications of recent developments in motion capture and pattern recognition on collecting field data of warfighter motion

To understand and assess dismounted infantry performance, it is necessary to be able to measure and report what a warfighter is physically doing while on exercise. For example, the ability to quantify changes in a warfighter's movement caused by wearing body armour or carrying additional equipment could help a military commander understand the effects of such protection and equipment on physical performance. Ultimately, this understanding could allow military leadership to make more informed decisions on what protection and equipment dismounted military members should wear/carry. Recent technological developments have given researchers new abilities to quantify warfighter movements in the field and predict potential changes caused by different body armour conditions.

Traditionally, motion capture has been conducted by using either an optical-based or electromagnetic-based motion capture system. Both of these types of systems are not generally suitable for data collection in the field because they have a limited motion capture volume; therefore, these types of systems have been limited to a laboratory setting. Using an IMU-based motion capture suit, the potential exists for full-body warfighter motion capture to be collected in the field because using such technology does not have the same restriction with respect to motion capture volume. However, there were a number of other technical limitations when using an IMU-based motion capture system that needed to be overcome. Recently, it appears as though those limitations have been overcome through the validation of an IMU-based suit for field-based motion capture specific to warfighting tasks.[29]

Although IMU-based motion capture provides a novel tool for researchers to collect motion in the field, the use of the technology remains labour-intensive. To expand the applications where field-based motion capture is possible, the ideal technology to collect motion capture data in the field would require only one sensor. Therefore, efforts continue to use pattern recognition algorithms to predict full-body motion capture through the use of a single sensor.[30]

With the technological advances described, there now exists the possibility of collecting large-scale datasets that represent dismounted military performance in the field, either in training or in operations. This new ability to quantify warfighter physical performance should lead to a better understanding of what constitutes positive and negative performance and lead to military leadership making more informed decisions on what protection and equipment to wear/carry in which situations.

CONCLUSION

This article provides six unique but related efforts bridging laboratory-based metrics with operational performance to provide specific, actionable outcomes for uniformed military personnel. Approaches to holistically assess individual warfighter and squad-based performance were discussed along with a framework for profiling variables that predict performance. Specific means and devices to quantify HRV in the field, movement mechanics and the impact of hearing acuity were presented. The combination of these topics suggests approaches, considerations and examples of integrated and holistic assessments of dismounted warfighter performance.

Acknowledgements The authors would like to acknowledge the warfighters and participants who participated in these efforts, making this work possible.

Contributors JS: Holistically quantifying dismounted Soldier performance. MOD, John Ramsay and Clifford Hancock: Emerging results from the field: quantifying team combat performance in dismounted infantry squads. SDM: Development of a framework to profile physiological and psychological variables to predict dismounted soldier performance. BS: Measuring the impact of hearing impairment and hearing protection devices on dismounted combat performance. KH: Wearing your heart on your sleeve (or wrist): wearable technologies for heart rate variability in the military – an update. TK: The implications of recent developments in motion capture and pattern recognition on collecting field data on soldier motion. JS acts as guarantor.

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants. The work summarised in the section 'Development of a framework to profile physiological and psychological variables to predict dismounted soldier performance' was approved by the UK Ministry of Defence Research Ethics Committee and has references 2024/MODREC/21 and 2190/MODREC/22. The work summarised in the section 'Emerging results from the field: quantifying team combat performance in dismounted infantry squads' was approved by the US Army Combat Capabilities Development Command Armaments Center Institutional Review Board, Study Number: 20-001. The studies summarised in the section 'Measuring the impact of hearing impairment and hearing protection devices on dismounted combat performance' were approved by the Walter Reed National Military Medical Center (WRNMMC) Institutional Review Board (IRB) (#372123 and #WRNMMC-2020-0287) and the Dwight D Eisenhower Army Medical Center IRB (#410543). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Commissioned; externally peer reviewed.

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