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Biomechanical and physiological biomarkers are useful indicators of military personnel readiness: a multi-institutional, multinational research collaboration

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ABSTRACT
A ubiquitous problem facing military organisations is musculoskeletal injury (MSKI) risk identification. Recently, two research groups, each with their own funding, collaborated to address this problem. Combining their respective areas of expertise in biomechanics and physiological biomarkers, the group explored this problem in the laboratory and in the field. They have developed a machine learning model in a US Marine Corps (USMC) officer cadet cohort that identifies MSKI risk from a single jump test, identified a minimum inertial measurement unit sensor array to quantity jump and squat performance and have identified sex differences in overuse, lower-limb injury risk. This machine learning model was able to correctly predict lift to place within 4 kg using a testing data set and less than 1 kg in the training set of data. Such collaborative approaches are encouraged to address complicated research problems. To assemble an effective team, consider forming groups that best complement each other's areas of expertise and prioritise securing separate funding to ensure each group can act independently. By doing this, the group has assessed the suitability and feasibility of various wearable technologies, used machine learning to gain insights into USMC physiological training adaptations, and developed an understanding of MSKI risk profiles within this cohort.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Musculoskeletal injury (MSKI) risk is a significant concern in military organisations, with previous studies focusing on biomechanics and physiological biomarkers.

WHAT THIS STUDY ADDS

⇒ This paper discussed the use of wearables, traditional biomarkers, and machine learning model approaches to predict MSKI risk. Additionally, there was a focus on sex differences in the injury risk of military personnel.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE, OR POLICY

⇒ The findings support the use of wearable technologies and machine learning in military training programmes to better understand and mitigate MSKI risk, potentially influencing future research and policy decisions.

INTRODUCTION
Answering complex research questions requires a team of researchers with appropriate expertise based on the research problem. Perhaps one of the most challenging research questions relates to musculoskeletal injury (MSKI) risk identification of military personnel throughout their career. The associated financial burden and impact on training days and force readiness have been well documented.[1 2] A simple PubMed search for 'musculoskeletal injuries military' results in over 1000 articles dating back to the 1970s. Despite this plethora of research, it is commonly accepted that MSKI is still a significant burden on military organisations around the globe. While there are many outstanding efforts by individual nations and research groups, there is still a need for a detailed investigation into how to identify risk factors that predispose personnel to injuries and to identify appropriate monitoring strategies. This paper presents a summary of specific research findings from two research groups in Australia and the USA that are currently collaborating to investigate MSKI in a military context. Throughout this research, the broader team has been granted access to US Marine Corps (USMC) cohorts in different training environments and this is the military context for the research results discussed below. Drawing together expertise in biomechanics and wearable technology (Australia) and physiological biomarkers and bone health (USA), the collective group have undertaken a wide range of laboratory-based and field-based studies that are exploring this complex problem through a wide lens. The first two sections will discuss physiological biomarkers and bone adaptations in USMC cohorts, this research was led by the USA-based research team. The next two sections of this paper will focus on the biomechanical monitoring and modelling and the use of wearables in a field environment to provide measures related to the kinematics and kinetics of movement; this element of the research was led by the Australian-based research team.

Physiological biomarker assessment of arduous military training and operations
Arduous military training offers unique opportunities to understand human physiological adaptations to military operational stress, such as sustained, high levels of physical activity and psychological

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and cognitive stress, combined with nutritional and sleep deficiencies. Compromised physical and cognitive performance degrading military readiness and increasing MSKI are all military operational concerns in which there are current research and development efforts to improve the understanding of risk mitigation strategies.[1 3] We have published a recent review that highlights a holistic, integrated and multidisciplinary approach, which includes biochemical measures, body composition and bone imaging, psychometric assessments, movement screening and physiological load monitoring with wearables.[4]

US Marine Officer Candidate School (OCS) is a physically rigorous military training school designed to select candidates with outstanding potential to lead Marines. OCS results in high rates of musculoskeletal injuries and attrition. Injury epidemiology data indicates that the injury rate is higher for women (~40%) than for men (~23%).[5] The most common anatomical location for injuries is lower body (foot, ankle, lower leg, and knee), followed by torso (abdomen, hip, lumbar spine, ribs, sacrum, and thoracic spine) and upper-body (hand and wrist, forearm, elbow, upper arm, or shoulder).[5] The specific OCS events where injuries were most prevalent for women were obstacle course (events requiring jumping and landing) conditioning hike, and junior's fartlek course and for men were obstacle course, endurance course, and conditioning hike.[5] Nearly 26% of all candidates attrit from the course (23% for male candidates and 38% for female candidates (unpublished data). The primary reasons for attrition are MSKI, non-MSKI medical, volitional withdrawal, not meeting USMC standards, and physical training (Forse *et al*, in review Military Psychology). Candidates with low body mass index (BMI), no prior military service, low resilience assessed via the Connor-Davison resilience scale, and low fitness levels (slow 3 mile run times) had an elevated risk of being discharged from OCS via all-cause attrition reasons (Forse *et al*, in review Military Psychology). Inflammation and oxidative stress were also measured, and results indicated that inflammation increased following OCS and, by the end of the course, ~38% of individuals had inflammation levels exceeding clinical cut-points.[6] Further, poor sleep going into OCS was associated with increased inflammation, while high fitness was associated with low inflammation levels.[6]

Force plate technology and markerless motion capture provide unique insights into movement quality. Using a cluster method analysis, Bird *et al*[7] identified countermovement jump (CMJ) movement strategies associated with MSKI risk. Specifically, the low-risk group (i.e., those at low risk of sustaining an MSKI) exhibited lowered maximum hip, knee, and ankle flexion during the CMJ compared with the moderate-risk and high-risk clusters.[7] Additionally, Bird *et al*[8] reported that while a proprietary MSKI health score and the DARI readiness and performance (DARI Motion, Overland Park, Kansas, USA) score were predictive of MSKI, after controlling for common MSKI risk factors (sex, age, and aerobic fitness), only the proprietary MSKI health score was predictive of injury.[8] However, the receiver operator curve characteristics and area under the curve performance remained poor for both the proprietary and DARI scores, demonstrating that they do not provide greater predictive ability than sex, age, and aerobic fitness.[8]

Wearable technologies have also been evaluated within the OCS programme. The Garmin Instinct Solar (Garmin, Olathe, Kansas, USA) was used to estimate daily mileage, daily steps, daily energy expenditure, and sleep. Results indicated that the daily training load was ~10–11 miles, ~20 259 steps, ~1367 kcal expended, 5 hour/day sleep, and an average daytime heart rate of 87 bpm.[9] Using inertial measurement units (IMUs) during a 9 mile rucksack carry revealed that both step count and intensity were greater in women than men suggesting greater mechanical load in women vs men (unpublished data).

Biomarkers of bone stress injury risk and bone adaptation during military training

Bone health is an important musculoskeletal consideration among military populations as training environments, which often expose Service Members to high-volume mechanical loading, can induce osteogenic adaptations[10 11] but may also induce a high rate of bone stress injuries (BSIs).[12 13] High rates of BSIs present a burden to the military system due to resultant economic costs, lost duty days, and attrition from training.[1] Additionally, BSIs disproportionately affect women[13] presenting a threat to female Service Member health and a barrier to sex integration efforts. As such, methods for monitoring bone health and identifying risk for BSIs in military personnel are of great interest for mitigating musculoskeletal injuries and maintaining medical readiness.

As part of the collaboration described here, skeletal adaptations and associations with BSI risk during 10 weeks of OCS were investigated. Specifically, peripheral quantitative CT (pQCT) was implemented to quantify volumetric bone mineral density (vBMD), geometry, and estimated strength of the tibia. Additionally, blood draws were performed to determine concentrations of bone turnover markers. In contrast to two-dimensional dual X-ray absorptiometry (DXA), which is often implemented in clinical settings, pQCT uses three-dimensional imaging to measure vBMD. This technology can discriminate between the cortical and trabecular compartments of a long bone and assess geometrical properties that influence bone strength.[14] As changes in bone structure can be slow to detect, monitoring concentrations of bone turnover markers is commonly employed in research and clinical practice for providing insight into short-term alterations in the processes of bone formation and resorption that may accumulate into structural changes.[15]

We previously demonstrated that baseline pQCT measures at predominantly cortical sites of the tibial diaphysis (i.e., 38% and 66% of total tibial length), indicative of increased bone width and strength were prospective predictors of BSI during OCS. Specifically, increased total area, periosteal circumference, robustness (defined as total area/tibia length), and estimated bending strength (SSI) were associated with a decreased likelihood of developing a BSI during training. Furthermore, these associations remained significant even after adjusting for the influence of sex, age, and BMI.[16] Awareness that bone health at the onset of a Service Member's military career can impact their future injury risk highlights the importance of optimising skeletal parameters early in life. For example, adolescence, when most bone mass is being accrued,[17] and prior to the start of initial military training have been identified as key windows of opportunity for promoting adaptive bone formation to develop a resilient skeleton that can protect against BSI during one's military career.[18]

Additional work is underway to assess longitudinal changes in vBMD, geometry, strength, and bone metabolism following successful completion of OCS. There is also an exploration into factors associated with potentially heterogeneous responses among individuals undergoing the same training programme. Of particular importance and interest is the influence of biological sex on bone adaptation following the 10-week military training course.

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Biomechanical biomarkers in the context of military operations and training

Real-time and continuous monitoring across several biomarker domains is considered the next fundamental step in enhancing soldiers' physical performance and reducing MSKI risk.[19] Traditional biomarkers, such as those explored in the previous sections of this paper, primarily concern objective measures of physiological status including blood, saliva, or urine.[20] Recently, human motion has been identified as a valuable data source capable of indicating health and performance status.[21] Motion-based (e.g., markerless motion capture) and wearable technologies (e.g., IMUs) fall under the 'biomechanical biomarkers' domain that provides objective assessments of motion. In the past, motion-based metrics have had limited utility to contribute to actionable decisions, potentially due to wearable devices operating on proprietary algorithms that are 'black boxes' to scientists. However, with advancements in hardware and analytics, researchers have sought to explore the richness of data that biomechanical biomarkers provide by exploring the relationships between these datasets and indicators of injury.[8 22] The utility of non-invasive biomechanical biomarkers to assess human performance provides a promising solution for identifying risk factors contributing to MSKI with ease in operational and training environments.

To appropriately quantify biomechanical biomarkers in the field, a clear understanding of the technology being used is required. By using established methods that work well within a laboratory environment, we can incrementally adapt and optimise them for applications in field-based environments. Ultimately, this will inform the down selection of key performance variables indicative of MSKI risk and the most reliable and valid methods of assessment in dynamic military setting.

Considering basic screening metrics, body composition changes (e.g., reductions in fat mass, increases in lean mass) are highly associated with increased MSKI risk due to the intense physical demands of military training and during operations.[23] Recent 3D scanning technologies (Styku 3D body scanner, Model S100X, Styku, Los Angeles, USA) claim to provide body composition estimates equivalent to those from gold standard DXA.[24] Despite showing highly reliable outputs, results should be interpreted with caution as there are clear limitations to the validity of specific measures; segment circumferences and lean muscle mass were valid, but segment lengths, body fat and bone measures were not. Notably, measures from individuals with ≥70.9 kg body mass and >1.70 m height had good agreement with the DXA gold standard (unpublished data).

Objective measurements of dynamic movements provide high-fidelity data but are time-consuming and require specific technical expertise. Optical motion capture (OMC) is the gold standard for assessing kinetic and kinematic motion. However, recent technologies including markerless motion capture and wearable sensors (IMU) offer non-intrusive, field-deployable solutions. For example, the VALD Humantrak system (VALD Performance, Brisbane, QLD, Australia) uses a single infrared camera to assess static and dynamic range of motion (ROM). Results demonstrated this system can produce highly reliable outputs, with the most reliable being shoulder adduction and hip flexion peak ROM values regardless of whether body armour was worn.[25] Relatedly, IMU sensors have been able to reliably replicate knee and ankle joint ROM to a similar standard as OMC measures in military-relevant dynamic movements.[22] Interestingly, these same sensors have been shown to identify hip and knee ROM during gait (loaded and unloaded) but appear to be unable to replicate lab-level kinematic waveform measures compared with OMC.[26] Though there is still work to be completed to truly understand the capabilities of biomechanical biomarkers, promising progress has been made and important considerations have been identified for conducting ecologically valid health, performance, and readiness assessments. This next section will explore the use of IMUs for the assessment of load carriage, with a focus on moving the measurement of movement quality outside of a laboratory environment.

Use of IMUs to quantify in-field biomechanics of military personnel

While the biomechanical adaptations that occur as a consequence of military-specific demands (e.g., the addition of body-borne loads) have been quantified in laboratory environments using OMC, they often fail to elicit physical and cognitive perturbations that are experienced in real-world scenarios. There is a need to bridge the gap between data from a laboratory, and what can be collected in the field. Technological advancements have led to exploration into the implementation of wearable sensors, such as IMUs. An array of sensors can estimate joint and whole-body kinematics, while one or two sensors may serve as surrogate measures of deleterious ground reaction forces, and the ability to attenuate these forces, that occur with the addition of load.[27–29] While a commercially available IMU suit may be able to quantify kinematics during military-specific movements in a laboratory, its application in the field may be cumbersome.[27] Implementing a reduced number of wireless sensors may be a strategy to employ this novel technology in tactical training environments.

A novel, minimal sensor approach has been used to quantify kinematics during strongman events such as the atlas stone lifts and yoke walks.[28] There may be an ability to apply this strategy to quantify kinematics during a bodyweight squat and CMJ—both discrete tasks that are common for injury screening and performance metrics.[22] Using a set of wireless IMUs placed on the lower extremity, hip and knee joint ROM are estimated when compared with the industry gold standard of 3D OMC. However, implementing this system in a gait task results in significant differences between systems. Moreover, kinematics estimated by IMUs while walking are also not sensitive to changes in movement patterns that occur as a consequence of grade (uphill, downhill, and flat) or the addition of body-borne load (23 kg).[26]

As such, it may be that researchers should move away from trying to replicate laboratory metrics with wearable sensors in a real-world scenario and instead turn their attention to what other metrics may provide actionable data. As peak accelerations are closely related to ground reaction forces, there is an opportunity to explore the influence of military-specific demands on IMU acceleration variables (e.g., peak acceleration and attenuation, i.e., how much signal is absorbed as it travels through the body).[29] While increasing speed increases peak accelerations at the foot and pelvis, it reduces the attenuation between the two sensors.[30]

While increasing speed increases peak accelerations at the foot and pelvis, it reduces the attenuation between the two sensors.[29] Conversely, load reduces peak accelerations at the foot and the pelvis but increases the amount of the signal that is attenuated between the two sensors.[30] When estimating attenuation metrics over the course of a kilometre, the addition of load lowers the amount attenuated per kilometre. When investigating the influence of grade, uphill attenuation is the lowest compared with flat and downhill, while downhill has the greatest attenuation compared with flat and uphill.[30]

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RECOMMENDATIONS

Findings from this collaborative research effort can provide several recommendations for USMC leadership: (1) further occupational-specific screening, serial measurements, and/or load exposure should be used to refine future MSKI risk models, (2) as few as two IMUs can be used to estimate loads associated with the physical demands placed on those undertaking military training like that observed by the research team, (3) preparatory training plans that include relevant fitness training may help to tolerate the physical demands of military training, (4) the higher mechanical loads in women, compared with men, could be managed via recovery period between events, (5) interventions to modify movement patterns to improve strength and power could reduce MSKI and (6) ultimately, information can be provided to training staff to make informed decisions regarding training volume and mode in a way that may reduce incidence rates of MSKI in military personnel.

CONCLUSION

Musculoskeletal injuries continue to place financial and personnel readiness burdens on military organisations around the world.[1 2] Despite the decades of research dedicated to this important topic, the identification of agreed, definitive risk factors and agreement on a standardised monitoring approach remains an active area of research. Recently, two research groups, one from Australia and one from the USA, have been working collaboratively to investigate this issue through an interdisciplinary, multi-institution approach. The collective research team has used their specific areas of expertise in biomechanics, wearable technologies, extracellular biomarkers, and physiology to understand the problem and find solutions. To date, they have used machine learning approaches to identify MSKI risk in a USMC officer cadet cohort by analysing the CMJ performance.[7] They have developed a minimum IMU sensor array to quantify jumping and squat performance as well as lower limb ROM during locomotion.[22 26] The research group has also identified sex differences in overuse lower-limb injuries in the USMC officer cadet cohort.[5] Research groups are encouraged to work collaboratively to address complicated research problems. By considering which groups best complement each other's areas of expertise, not replicates; a truly collaborative approach to research in this manner can have a multiplier effect when it comes to research outputs that provide answers to the research questions and securing funding to support the ongoing research of multiple groups.

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