Biomechanical Differences between Normal Walking and Tactical Walking: Guiding Exoskeleton Development to Enhance Physical Capabilities of Tactical Athletes

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Abstract

BACKGROUND: Exoskeletons for military and civilian tactical athletes are potentially beneficial tools to increase survivability and enhance operational capabilities, but are largely designed from basic movements, such as normal walking. In order to provide exoskeleton developers with the most comprehensive information to design these devices and mitigate restriction of the user's abilities to execute occupational duties, it is warranted that tactical walking movement patterns be investigated. METHODS: Twenty-four male tactical athletes (22 active duty Army Soldiers, 2 civilian SWAT operators; age: 23.83 ± 5.47 years; height: 1.80 ± 0.08 m; weight: 81.04 ± 7.87 kg) participated. Tactical athletes performed normal walking and tactical walking (i.e. walking while maintaining weapon aim or 'shoot on the move' [SM]) along a 15-meter path. Both tasks were completed under three speed conditions: (1) self-selected slow speed, (2) 1.12 m/s , and (3) self-selected fast speed. Three trials were completed for each speed and speeds were completed from slowest to fastest. Lower extremity kinematics were collected via wireless inertial measurement units (myoMotion, Noraxon ISA, Inc., Scottsdale, AZ).

Spatiotemporal parameters were collected via optical detection system (OptoGait, Microgate, Mahopac, NY). Repeated measures 2 (walking task) x 3 (speed) ANOVAs were performed for dependent variables. Tukey HSD post hoc pairwise comparisons were performed for significant effects. Alpha level was set *a priori* at $p \leq .10$. RESULTS: Main effects of walking task and speed condition were observed on lower extremity kinematics where tactical athletes exhibited larger flexion angles during SM than during normal walking ($p < .01$) and larger flexion angles during faster speeds compared to slower speeds ($p < .01$). Longer strides and less time spent in double limb support were observed during faster speeds compared to slower speeds ($p < .01$). A walking task main effect was observed on stride length were tactical athletes adopted shorter strides during SM than normal walking ($p < .01$). CONCLUSION: Military and law enforcement personnel exhibit different movement patterns during tactical walking compared to normal walking. These modified gait patterns are also influenced by speed of movement. These tactical athletes perform occupationally-relevant movements and tasks that may not directly translate to basic movements. Therefore, it is critical that information on these occupationally-relevant movements be accessible to exoskeleton designers to build optimum control systems that will aid and not hinder tactical athletes in their roles to serve and protect. Outside of tactical populations, exoskeletons for rehabilitation applications would potentially benefit from understanding biomechanics of more complex movements to design more robust control systems when used for general populations post-injury, such as spinal cord injuries or stroke patients. Findings from our study highlight fundamental differences between basic and complex movements which translate across multiple domains to enhance human performance.

Introduction

Civilian (e.g. law enforcement, SWAT) and military (e.g. infantry Soldiers, Special Operation Forces [SOF] Operators, and Special Reaction Teams [SRT]) tactical athletes are personnel who engage in tactical and occupational duties aimed to protect the community and their country.[1] Survivability and lethality are dependent, in part, on the ability of tactical athlete to perform tasks which are necessary to accomplish occupational duties at optimal performance [2] and to protect themselves or others from harm. Tactical athletes are often subjected to high-risk environments that require a greater demand for mobility negotiation and adaptability to unpredictable situations than the demands of daily activities.[3-6] Although they perform basic movements, such as walking, during duty, tactical athletes also perform operationally relevant movements, such as walking while maintaining weapon aim (i.e. 'shoot on the move'); these specialized movements may not adopt the same movement patterns as those of basic movements used in daily activity outside of tactical duties.

Tactical athletes require unique and specialized capabilities from exoskeletons in order to fulfill their operational duties without the device hindering or impinging on natural movement. Since very little information is available to developers on the movement patterns of operationally relevant tasks, building exoskeletons for these populations poses a challenge. The preliminary assumption from developers is that basic movements (i.e. walking) directly translate to operationally relevant movement (i.e. 'shoot on the move'), which may not be an accurate or appropriate conclusion. Research on operationally relevant tasks and their fundamental movement patterns warrant further investigation to lay groundwork for developers to build more robust control systems and devices that encompass both basic and operationally relevant tasks.

During ‘shoot on the move’ (SM), tactical athletes engage in a crouched gait pattern where the lower extremities are in a sustained flexed state.[7] This movement pattern minimizes weapon trace motion, or excessive movement of the weapon, to improve shooting accuracy. A consistent and controlled state of hip and knee flexion during SM also minimizes the tactical athlete’s center of mass. Compared to normal gait, crouched gait, like that during SM, induces increased knee flexion throughout the stance phase.[8] A fundamental component of SM is carrying a weapon often in both hands which restricts arm swing. Minimal arm swing while holding a weapon decreases axial rotation and lateral bending during SM compared to normal walking.[9]

Currently, there is limited research available which examines the biomechanics and fundamental movement patterns of operationally relevant tasks. SM and other relevant tasks are core tactical movements implemented to better prepare for the operational environment. Information on movement patterns and characteristics of SM are currently unavailable or limited to guide training, return-to-duty protocols, and exoskeleton development; disregarding unique movement characteristics of operationally relevant movements in these domains may ultimately lead to tactical athletes not being as prepared for occupational duties, premature return-to-duty, or devices that limit the user’s abilities and restrict execution of occupational duties. Findings from this study will provide fundamental and novel information on the characteristic movement patterns of SM as compared to normal walking.

It is important to identify similarities and differences between basic and tactical movements to better guide training paradigms, return-to-duty programs following injury, and physical augmentation device development. Therefore, the purpose of this study was to characterize and identify lower extremity kinematic and spatiotemporal differences in movement patterns between normal walking and walking while maintaining weapon aim.

Methods

Twenty-four male tactical athletes (22 active duty Army Soldiers, 2 civilian SWAT operators; age: 23.83 ± 5.47 years; height: 1.80 ± 0.08 m; weight: 81.04 ± 7.87 kg) participated. All tactical athletes were in good health and successfully qualified with a rifle within a year of participating in the study. Exclusion criteria included: (1) self-reported medical profile for illness or injury, (2) existing pain or injury in the legs, back, neck, or shoulders, (3) profile or restrictions against aerobic activity, load carrying activities or firing of small arms, (4) medical conditions or current medications which affect balance, (5) known allergies to latex or adhesives, and (6) prior convictions of a misdemeanor crime of domestic violence. To ensure the participants' rights were protected, the study protocol was approved by the U.S. Army Research Laboratory institutional review board. All participants signed informed consent prior to testing. Participants were briefed on the conduct of testing and all standard operating procedures and safety requirements relative to the shooting range and weapon system prior to testing. A range safety officer was present at all times during testing.

Tactical athletes performed two walking tasks: (1) normal walking and (2) tactical walking (i.e. walking while maintaining weapon aim or 'shoot on the move' [SM]) along a 15-meter path on grass at an outdoor shooting range. Cones were placed along the path to identify events of the task (e.g. start, engage weapon, stop) (Figure 1). An E-type silhouette (101.6 cm height x 49.5

cm width) was positioned at the end of the path approximately 25 meters from the start cone of the path to represent the aim point during SM. During normal walking, participants were instructed to engage in normal walking patterns while ambulating the length of the path from the start cone to the end cone.

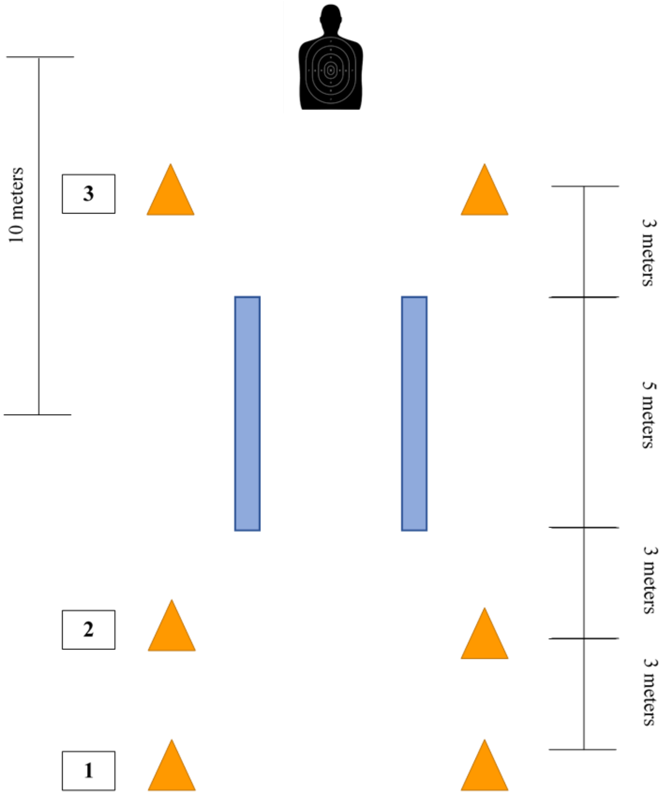


Figure 1. Participants began the task standing between the cones at the start position (1) and ended the task after passing through the cones at the stop position (3). During SM, participants were instructed to maintain weapon aim with the target (E-type silhouette, black) at the engage cone (2). Participants passed through the optical tracking system to collect spatiotemporal parameters for all tasks (blue rectangles).

During SM, participants began at the start cone with the weapon (5.56 x 45 mm chambered rifle with a red dot optic) in a low-ready position (Figure 2). Normal walking with the weapon in low-ready was completed from the start cone to the engage cone. At the engage cone, instructions were given to get into the engage position (i.e. maintain weapon aim at the target) to simulate

SM (Figure 2). Participants remained in the engage position from the engage cone to the stop cone. Normal walking was completed prior to SM for all participants.

Figure 2. Operator in a low-ready position (left) and in an engaged position (right) during SM.

Both tasks were completed under three speed conditions: (1) self-selected slow speed, (2) 1.12 m/s , and (3) self-selected fast speed. Normal gait speeds range from 1.05 to 1.43 m/s for healthy adults.[10,11] A fixed normal speed of 1.12 m/s was chosen as the best representation of a normal speed at which tactical athletes would engage in ‘shoot on the move’. Prior to testing, participants were instructed to choose one slow and one fast walking speed which reflect execution of the SM task during operational situations. Speeds were recorded as the slow and fast self-selected speeds. Participants completed three trials of each speed from slowest to fastest speed.

Wireless inertial measurement units (IMU) (myoMotion, Noraxon ISA, Inc., Scottsdale, AZ) were placed bilaterally on the feet, shanks (tibia), and thighs as well as on the posterior pelvis (sacrum), and trunk (cervical 7). An additional IMU was placed on the weapon barrel. Lower-extremity kinematics were collected via IMUs (sampling rate: 200 Hz). Peak hip flexion angle, peak knee flexion angle, and peak ankle dorsiflexion angle in the stance phase were calculated for each gait cycle. Peak values were averaged across all gait cycles for each trial, then averaged across three trials for an overall condition mean. Participants completed tasks through an optical detection system (OptoGait, Microgate, Mahopac, NY) to quantify spatiotemporal parameters. Body height (BH) normalized stride length (% BH) and time spent in double limb support (% gait cycle) were calculated across each gait cycle over a single trial.

Repeated measures 2 (normal walking, SM) x 3 (speed condition) ANOVAs were performed to test the effects of walking task and speed condition on kinematic and spatiotemporal parameters. Post hoc pairwise comparisons were conducted using Tukey HSD corrections for significant main effects. Alpha level was set *a priori* at $p \leq .10$. All analyses were conducted in RStudio v3.6.1 (2019) using the anova() and TukeyHSD() functions for models.

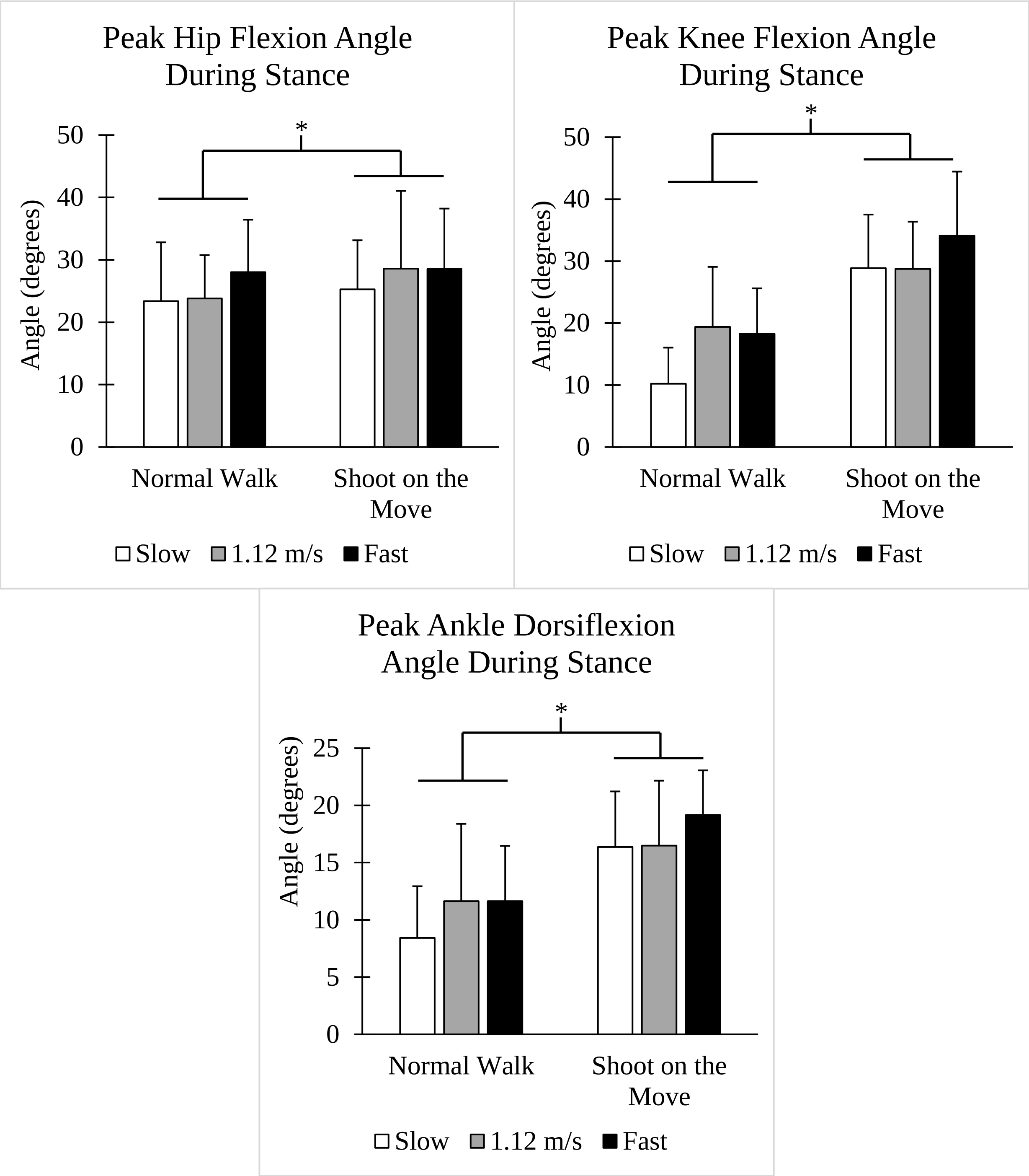
Results

Kinematics

Main effects of walking ($p = .01$) and speed ($p < .01$) conditions were observed on peak hip flexion. Tactical athletes exhibited larger peak hip flexion angles during ‘shoot on the move’ (27.47°) than during normal walking (25.07°). Peak hip flexion angles were larger at fast speed (28.29°) compared to slow speed (24.34°) ($p < .01$). No other significant post hoc speed pairwise comparisons were observed. No significant walking x speed interactions were observed (Figure 3).

A significant walking x speed interaction was observed on peak knee flexion angle (p < .01). Tactical athletes exhibited larger peak knee flexion angles during ‘shoot on the move’ than during normal walking regardless of speed (p < .01). For both normal walking and ‘shoot on the move’ larger peak knee flexion angles were observed at fast speed compared to slow speed (p < .10). During normal walking, tactical athletes exhibited larger peak knee flexion angles at 1.12 m/s compared to slow speed (p < .01). No differences were observed between peak knee flexion angles at 1.12 m/s and fast speed while walking normally (p = .99). During ‘shoot on the move’, tactical athletes exhibited larger peak knee flexion angles at fast speed compared to 1.12 m/s (p < .01). No differences were observed between peak knee flexion angles at 1.12 m/s and slow speed during ‘shoot on the move’ (p = .93) (Figure 3).

Main effects of walking (p = .01) and speed (p < .01) conditions were observed on peak ankle dorsiflexion. Tactical athletes exhibited larger peak ankle dorsiflexion angles during ‘shoot on the move’ (17.33°) than during normal walking (10.57°). Peak ankle dorsiflexion angles were larger at fast speed (15.40°) compared to slow speed (12.40°) (p < .01). No other significant post hoc speed pairwise comparisons were observed. No significant walking x speed interactions were observed (Figure 3).



Peak Hip Flexion Angle During Stance

Peak Knee Flexion Angle During Stance

Peak Ankle Dorsiflexion Angle During Stance

Figure 3. Peak hip (top left), knee (top right), and ankle (bottom) flexion angles during stance phase of normal walking and 'shoot on the move' at three speeds. Significant walking condition main effect is indicated by (*) at a level of .10.

Spatiotemporal

A significant walking x speed interaction was observed on stride length (p < .01). Tactical athletes exhibited shorter strides during 'shoot on the move' (68.62 % BH) than during normal walking (79.45 % BH) regardless of speed condition (p < .01). For both normal walking and 'shoot on the move', longer strides were observed as speed increased from slow to 1.12 m/s to fast (p < .01) (Figure 4).

Only a significant speed condition main effect was observed on time spent in double limb support (p < .01) which decreased as walking speed increased (slow: 48.59%; 1.12 m/s: 44.94%; fast: 39.97%) (Figure 4).

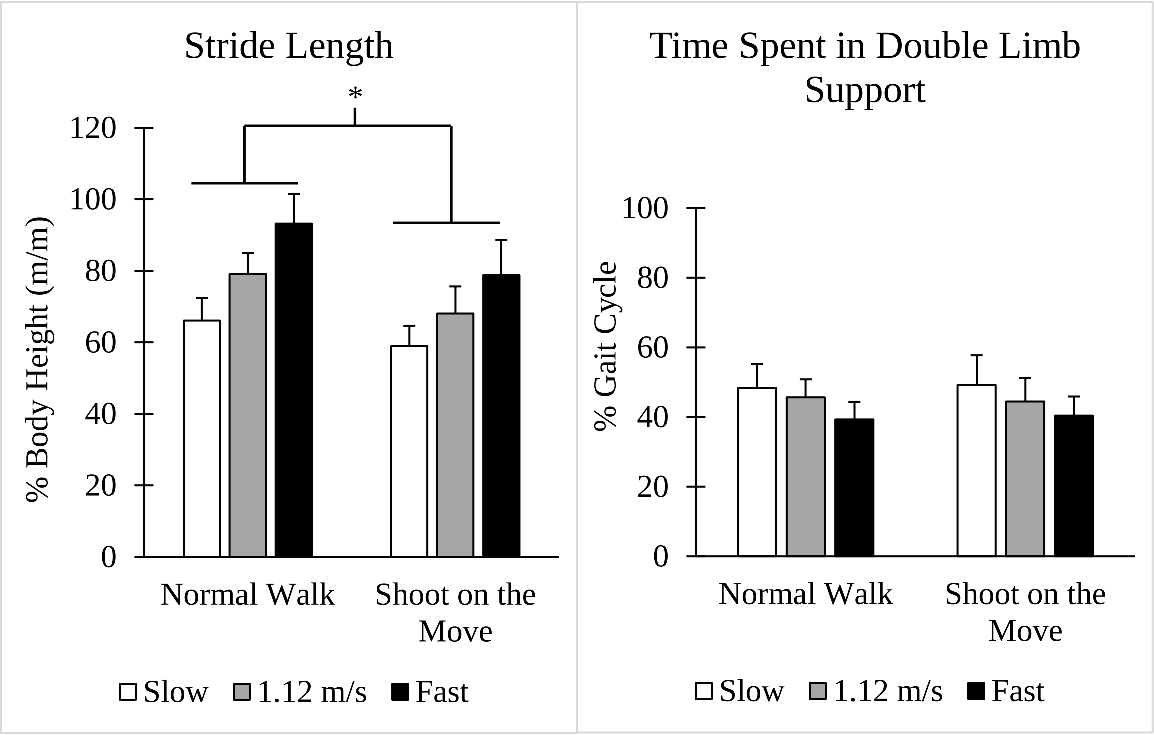


Figure 4. Stride length (left) and time spent in double limb support (right) of normal walking and 'shoot on the move' at three speeds. Significant walking condition main effect is indicated by (*) at a level of .10.

Discussion

This study aimed to identify lower extremity kinematic and spatiotemporal parameter differences between normal walking and walking while maintaining weapon aim (i.e. ‘shoot on the move’). Findings revealed that tactical athletes engaged in more flexed lower extremity movement patterns and shorter strides during ‘shoot on the move’ than during normal walking. Performing ‘shoot on the move’ at faster speeds elicited more flexed lower extremities, longer strides, and less time spent in double limb support. This is the first study to the authors’ knowledge that characterizes gait-related movement patterns of a common operationally relevant task. Findings from this study highlight the significance of identifying differences in movement patterns for comprehensive designs of future exoskeleton and physical augmentation device development.

Physical augmentation devices and exoskeletons for tactical athletes are potentially beneficial tools to increase survivability and enhance operational capabilities. Efforts led to build these devices have cost upward of $80 million;[12-14] however, experts suggest these devices may require as much as $500 million for designs to meet occupational demands.[14] Many device control systems have been designed from basic movements, such as normal walking. Building control systems and modeling for basic movements are effective for industrial or rehabilitation platforms but may not appropriately account for applications in the tactical setting. Occupational demands of tactical athletes require specialized movements, such as ‘shoot on the move’, that may not directly translate to basic movements. Findings from this study support that there are significant differences in movement characteristics between normal walking and ‘shoot on the move’, even if both tasks fall under the generalized gait task identification.

Lower limb movement during normal walking exhibits an inverted pendulum pattern.[15] Unlike normal walking, ‘shoot on the move’ is a gait-related task that produces a plateau pattern where the center of mass minimally changes vertical position. Although prompted by different causes, children with cerebral palsy exhibit similar hip and knee mechanics during gait as those of ‘shoot on the move’. As this is the first investigation of ‘shoot on the move’ biomechanics, research on cerebral palsy provides insight into possible differences between crouch gait (similar to that of ‘shoot on the move’) and normal gait. The very nature of ‘shoot on the move’ requires constant uninterrupted flexion of the hips and knees which limits the range of motion experienced by the lower extremity joints during movement. Restricted lower extremity range of motion presents changes in joint mechanics compared to normal gait which is not constrained by constant hip and knee flexion. Crouched gait induces increased knee flexion throughout the stance phase compared to normal gait as confirmed by results from our study.[8] Due to increased lower extremity joint flexion, there is also a reduction in the ability for these joints to generate extension accelerations and moments, which induces greater capacity of muscles to generate forces to maintain the crouched posture.[8,16-18] Adjustments to joint loading and ground reaction forces from normal walking warrant further investigation of ‘shoot on the move’ to better identify differences between these tasks.

The main objective of ‘shoot on the move’ is to minimize vertical movement of the upper body to maintain weapon aim on a target. Larger hip, knee, and ankle flexion angles exhibited during ‘shoot on the move’ compared to normal walking support this objective so as to lower the body’s center of mass. Similarly, tactical athletes adopted shorter strides during ‘shoot on the move’ compared to normal walking to maintain stability. Decreased stride length has been reported to be a mechanism to position the center of mass closer to the moving base of support [19] and minimize risk of falling.[20,21] These are critical factors during ‘shoot on the move’ where an unpredictable environment warrants alertness and stability when possible. A key difference between normal walking and ‘shoot on the move’ is the restriction of arm swing where tactical athletes are holding a weapon. Martin and Nelson[22] identified this restriction in arm swing as a source in reducing a tactical athlete’s ability to take longer strides, more specifically when carrying lighter loads. Although load carriage was not investigated in this study, our findings support those of Martin and Nelson[22] where shorter strides were observed during ‘shoot on the move’ with restricted arm swing compared to normal walking with arm swing.

Findings revealed that gait speed significantly influenced movement patterns during ‘shoot on the move’. It has been well reported that speed affects kinematics and spatiotemporal parameters[23-30] which supports our findings. Larger flexion angles, longer strides, and less time spent in double limb support were observed while walking at a faster speed. The positive relationship between stride length and joint flexion angles seem to indicate that a more crouched position is adopted by tactical athletes during faster speeds to increase gait stability. As speed increases, less time is spent in double limb support suggesting that a quick transition of leading leg to lagging leg is necessary to maintain stability at a fast pace. Exoskeleton developers may consider control systems that need to be adapted to speed of movement as supported by findings from this study. This suggests that both the type of movement and speed of movement influences hip and knee flexion angles differently. Current systems may only consider one factor rather than both movement type and speed, which could hinder capabilities to perform movements necessary during occupational duties.

This study was not without its limitations. Although no female operators participated and only two of the participants were non-military personnel (SWAT), we believe these findings can be generalizable to the entire tactical athlete population as ‘shoot on the move’ is a common occupational task regardless of sex or personnel. Years of experience or years served were not included in the analyses as a possible covariate, which may likely influence movement performance. Regardless of years of experience or years served, profiling the general characteristics of ‘shoot on the move’ provides fundamental information to better design exoskeletons for future use in the tactical athlete population.

Conclusion

These biomechanical differences normal walking and ‘shoot on the move’ may guide changes in exoskeleton design considerations to account for variation in movement profiles between such tasks. In order to best prepare and protect tactical athletes, operationally relevant movements must be considered when designing exoskeletons for occupational use. Further investigation is warranted to provide a more robust analysis of changes in tactical movements.

References

1. Joseph A, Wiley A, Orr R, et al. The impact of load carriage on measures of power and agility in tactical occupations: A critical review. *Int J Environ Res Public Health.* 2018;15:88.

2. Scherer MR, Weightman MM, Radomski MV, et al. Returning service members to duty following mild traumatic brain injury: Exploring the use of dual-task and multitask assessment methods. *Phys Ther.* 2013;93:1254-1267.

3. Scribner DR, Harper WH. The effects of mental workload: Soldier shooting and secondary cognitive task performance. ARL-TR-2525. Aberdeen Proving Ground, MD,

U.S. Army Research Laboratory, 2001. Available at http://www.dtic.mil/dtic/tr/fulltext/u2/b271975.pdf; Accessed 02 Feb 2018.

4. Frykman PN, Harman EA, Pandorf CE. Correlates of obstacle course performance among female soldiers carrying two different loads. Natick, MA, U.S. Army Research Institute of Environmental Medicine, 2001. Available at http://www.dtic.mil/docs/citations/ADP010994; Accessed 15 Sept 2018.

5. Collingwood T, Hoffman R, Smith J. Underlying physical fitness facors for performing police officer physical tasks. *Police Chief*, 2004;71:32-37.

6. Hunt AP, Tofari PJ, Billing DC, et al. Tactical combat movements: inter-individual variation in performance due to the effects of load carriage. *Ergonomics.* 2016;59:1232-1241.

7. Talarico M, Neugebauer J. Spatiotemporal and lower body kinematic differences between normal walking and walking while holding weapon aim. *J Sci Med Sport.* 2017;20:S174.

8. Hicks JL, Schwartz MH, Arnold AS, et al. Crouched postures reduce the capacity of muscles to extend the hip and knee during the single limb stance phase of gait. *J Biomech.* 2008;41:960-967.

9. Callaghan JP, Patla AE, McGill SM. Low back three-dimensional joint forces, kinematics, and kinetics during walking. *Clin Biomech.* 1999;14:203-216.

10. Al-Obaidi S, Wall JC, Al-Yaqoub A, et al. Basic gait parameters: a comparison of reference data for normal subjects 20 to 29 years of age from Kuwait and Scandinavia. *J Rehabil Res Dev.* 2003;40:361-366.

11. Oberg T, Karsznia A, Oberg K. Basic gait parameters: reference data for normal subjects, 10-79 years of age. *J Rehabil Res Dev.* 1993;30:210-223.

12. Leonard M. Strengthening the soldier with exoskeletons. *Defense Systems*, 2018.

13. Harvard's Wyss Institute awarded DARPA contract to further develop Soft Exosuit. 2014. Available at https://wyss.harvard.edu/darpa-contract-to-further-develop-soft-exosuit/; Accessed 04 Oct 2018.

14. Cornwall W. Feature: Can we build an 'Iron Man' suit that gives soldiers a robotic boost? *Science*, 2015.

15. Cavagna GA, Heglund NC, Taylor CR. Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *Am J Physiol.* 1977;233:R243-261.

16. Hsu AT, Perry J, Gronley JK, et al. Quadriceps force and myoelectric activity during flexed knee stance. *Clin Orthop Relat Res.* 1993:254-262.

17. Rosenthal RK, Levine DB. Fragmentation of the distal pole of the patella in spastic cerebral palsy. *J Bone Joint Surg Am.* 1977;59:934-939.

18. Lloyd-Roberts GC, Jackson AM, Albert JS. Avulsion of the distal pole of the patella in cerebral palsy. A cause of deteriorating gait. *J Bone Joint Surg Br.* 1985;67:252-254.

19. Bhatt T, Wening JD, Pai YC. Influence of gait speed on stability: recovery from anterior slips and compensatory stepping. *Gait Posture.* 2005;21:146-156.

20. Hak L, van Dieen JH, van der Wurff P, et al. Walking in an unstable environment: strategies used by transtibial amputees to prevent falling during gait. *Arch Phys Med Rehabil.* 2013;94:2186-2193.

21. Hak L, Houdijk H, Beek PJ, et al. Steps to take to enhance gait stability: the effect of stride frequency, stride length, and walking speed on local dynamic stability and margins of stability. *PLoS ONE.* 2013;8:e82842-e82842.

22. Martin PE, Nelson RC. The effect of carried loads on the walking patterns of men and women. *Ergonomics.* 1986;29:1191-1202.

23. Schwartz MH, Rozumalski A, Trost JP. The effect of walking speed on the gait of typically developing children. *J Biomech.* 2008;41:1639-1650.

24. Chehab EF, Andriacchi TP, Favre J. Speed, age, sex, and body mass index provide a rigorous basis for comparing the kinematic and kinetic profiles of the lower extremity during walking. *J Biomech.* 2017;58:11-20.

25. Benedetti MG, Catani F, Leardini A, et al. Data management in gait analysis for clinical applications. *Clin Biomech.* 1998;13:204-215.

26. Robinson JL, Smidt GL. Quantitative gait evaluation in the clinic. *Phys Ther.* 1981;61:351-353.

27. Latt MD, Menz HB, Fung VS, et al. Walking speed, cadence and step length are selected to optimize the stability of head and pelvis accelerations. *Exp Brain Res.* 2008;184:201-209.

28. Lelas JL, Merriman GJ, Riley PO, et al. Predicting peak kinematic and kinetic parameters from gait speed. *Gait Posture.* 2003;17:106-112.

29. Cofré LE, Lythgo N, Morgan D, et al. Aging modifies joint power and work when gait speeds are matched. *Gait Posture.* 2011;33:484-489.

30. Hanlon M, Anderson R. Prediction methods to account for the effect of gait speed on lower limb angular kinematics. *Gait Posture.* 2006;24:280-287.