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Air Assault Soldiers Demonstrate More Dangerous Landing Biomechanics When Visual Input Is Removed

Yungchien Chu, MS; Timothy C. Sell, PhD*; John P. Abt, PhD*; Takashi Nagai, PhD*; Jennifer Deluzio, MS*; COL Mark McGrail, MC USA†; LTC (P) Rusty Rowe, MC USA‡; COL Brian Smalley, MC USA§; Scott M. Lephart, PhD**

ABSTRACT Soldiers are subjected to increased risk of musculoskeletal injuries in night operations because of limited visual input. The purpose of this study was to determine the effect of vision removal on lower extremity kinematics and vertical ground reaction forces during two-legged drop landings. The researchers tested 139 Air Assault Soldiers performing a landing task with and without vision. Removing visual input resulted in increased hip abduction at initial contact, decreased maximum knee flexion, and increased maximum vertical ground reaction force. Without vision, the timing of maximum ankle dorsiflexion for the left leg was earlier than the right leg. The observed biomechanical changes may be related to the increased risk of injury in night operations. Proper night landing techniques and supplemental training should be integrated into Soldiers' training to induce musculoskeletal and biomechanical adaptations to compensate for limited vision.

INTRODUCTION

Landing is a task widely performed in Soldiers' physical and tactical training as well as tactical operations. Examples include exiting a vehicle (from a height), traversing a ditch, and climbing over an obstacle. Landing, even from low heights, typically induces high ground reaction forces (GRFs), which are transferred up of the kinetic chain of the lower extremities[1] and have been linked to musculoskeletal injuries in the lower body.[2] Noncontact knee injuries have been one of the most popular areas of research in sports medicine. Numerous studies have been attempted to identify risk factors and biomechanical characteristics of such injuries.[2–8] The knee has been reported as the most frequently injured body part, and accounted for 10 to 34% of all musculoskeletal injuries among different military groups, from Army Infantry to Naval Special Warfare trainees.[9] The frequency of ankle injury in military may be comparable or only secondary to the knee with 11 to 24% of all musculoskeletal injuries occurred at the ankle.[9] Lephart et al[5] suspected that ankle kinematics may have effects on the GRFs during landing. In simulated parachute landing, subjects who landed flat-footed demonstrated greater GRFs than those who landed with the ball of the foot at initial ground contact.[10]

*Neuromuscular Research Laboratory, Department of Sports Medicine and Nutrition, University of Pittsburgh, 3830 South Water Street, Pittsburgh, PA 15203.

†Blanchfield Army Community Hospital, 650 Joel Drive, Fort Campbell, KY 42223.

‡Walter Reed Army Medical Center, 6900 Georgia Avenue, Washington, DC 20307.

§Division Surgeon's Office, 6906 A Shau Valley Road, Fort Campbell, KY 42223.

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Soldiers can be viewed as tactical athletes. Unlike typical civilian athletes, Soldiers commonly perform their tasks with heavy equipment in challenging environments. Soldiers may need to perform tactical operations at nighttime for stealth and security purposes. Although darkness makes a Soldier harder to be detected by enemies, it also decreases or deprives their use of visual input when interacting with the environment. Even with facilitating equipment such as night vision goggles, the Soldier's visual input is still limited as compared to daytime. With limited vision, the vestibular system and the somatosensory system must assume greater demands to maintain Soldier's postural stability. It is questionable whether sufficient adaptations on these two systems have been induced via the Soldier's physical and tactical training.

In the military, most research examining the effect of night operation on injuries have focused on parachuting, during which 61 to 84% of injuries occurred at the moment of landing.[11,12] The relative risk of injury was reported between 1.94 and 3.13 at night, compared with daytime parachuting.[11,13] According to a review by Knapik et al[14], similar elevated risks of injury during night parachuting existed in airborne Soldiers of other countries: 2.4 in Israel, 4.1 in Belgium, and between 1.3 and 41.2 in United Kingdom. It is believed that limited visibility of the landing surface and perception of distance and depth contributed to the higher risk of injury.[14] Such mechanisms should apply to any general landing task with impaired vision. Some researchers have evaluated the landing biomechanics with the removal of visual input with inconclusive results.[15–18] Santello et al[16] found decreased maximum knee flexion and increased vertical ground reaction force (VGRF) without vision, whereas Liebermann and Goodman[15,18] found unchanged or decreased VGRF when blindfolded. Nevertheless, none of these studies involved military population. Unlike the general population, Soldiers have been trained for night operation; such training may induce certain adaptations. By observing Soldiers' night training in a qualitative task analysis, we determined that landing from a jump under low light conditions may be associated with increased risk of lower extremity injury.[19] It is unclear how the biomechanical variables change quantitatively in Soldiers when landing without vision and whether these potential changes would suggest increased risk of lower body injury.

Therefore, the purpose of this study was to investigate how the removal of visual input would affect the lower body kinematics and kinetics of Soldiers performing a landing task. We hypothesized that the removal of visual input would alter landing mechanics and increase GRFs.

METHODS

Subjects

A total of 139 male 101st Airborne Division (Air Assault) Soldiers (age: 28.5 ± 7.1 years, body height: 1.77 ± 0.08 m, body mass: 83.3 ± 13.5 kg) voluntarily participated in this study. Eligible subjects were 18- to 55-year-old males cleared for participation in daily physical and training activities. Exclusion criteria included history of concussion or mild head injury in the previous year, lower extremity or back musculoskeletal pathology that could affect the ability to perform the tests within this study in the past 3 months, history of lower extremity musculoskeletal surgery, or history of neurological or balance disorders. Informed consent was obtained before performance of any testing procedures. The current study was approved by University's Institutional Review Board, Eisenhower Army Medical Center, Army Clinical Investigation Regulatory Office, and Army Human Research Protection Office. All the tests were conducted at our Research Center for Injury Prevention and Human Performance, Fort Campbell, Kentucky.

Instrumentation

Six high-speed cameras (Vicon, Centennial, Colorado) operating at 200 Hz and two force plates (Kistler, Amherst, New York) operating at 1200 Hz were used to capture the kinematic and GRF data, respectively. The equipment was synchronized using Vicon Nexus software.

Procedures

Sixteen reflective markers were placed on subject's anatomical landmarks, including the anterior superior iliac spines, posterior superior iliac spines, lateral thighs, lateral knees, lateral shanks, lateral malleoli, calcanei, and second metatarsals. Subjects' anthropometric parameters were measured using an anthropometer (Lafayette Instrument, Lafayette, Indiana). A static trial was captured for each subject at the anatomical position and served as the baseline for joint angle calculations.

The subjects were then asked to perform two-legged drop landings from a 50-cm platform under two conditions: with visual input (WV) and no visual input (NV). For the NV condition, visual input was removed by using a blindfold (Figs. 1 and 2). In true training or combat environments, Soldiers may drop from higher heights such as the deck of an High

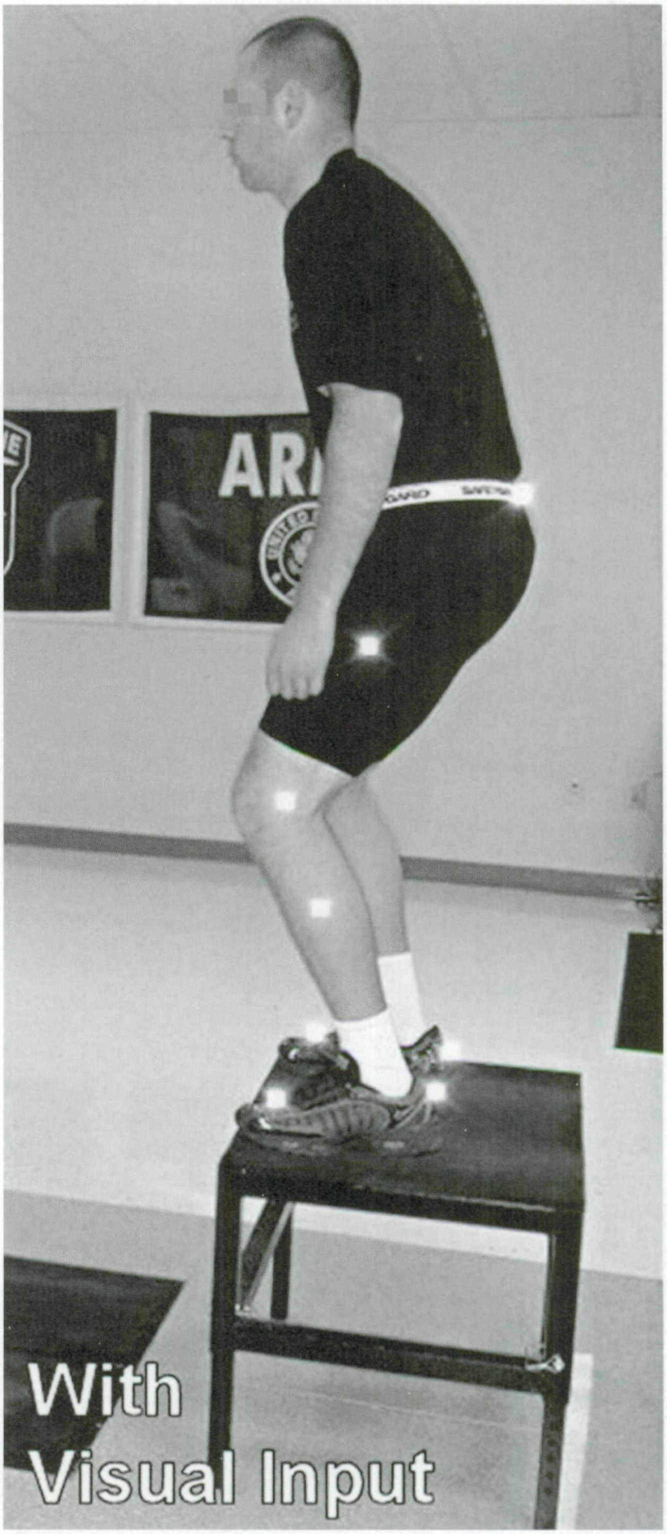

FIGURE 1. Drop landing WV.

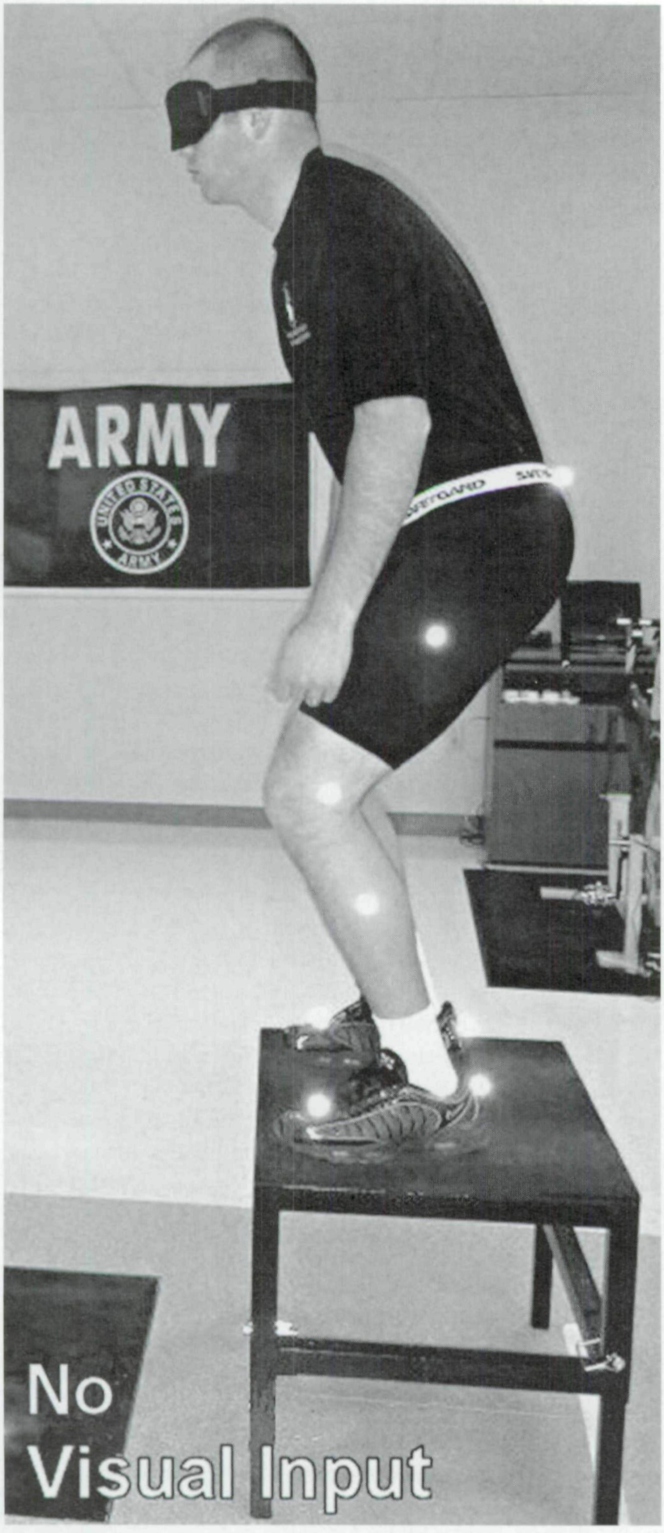

FIGURE 2. Drop landing NV.

Mobility Multipurpose Wheeled Vehicle (HMMWV) (84 cm) or an UH-60 Black Hawk Helicopter (115 cm). In our pilot study, raising the platform height from 50 to 100 cm resulted in an increased VGRF of 95.5% body weight (BW). Because of safety concerns related to the large increase in VGRF, the 50-cm platform height was chosen as this height is comparable to the median platform heights used in previous studies investigating the effects of vision removal.[15–18] The subjects were instructed to stand near the edge of the platform, drop off, land on both feet on the two force plates, and remain standing for 2 seconds after landing. The subjects were given at least three practice trials for each condition. Trials in which the subjects failed to regain balance or touched the ground off the force plates were rejected and replaced. Three successful trials were collected for each condition.

Data Reduction

Vicon Nexus software was used to reconstruct three-dimensional trajectories of the reflective markers. The trajectories were further smoothed with a general cross-validation Woltring filter.[20] The trajectories of the hip, knee, and ankle joint centers were estimated based on the marker locations and anthropometric parameters, according to Vicon's Plug-in Gait model (Vicon). The accuracy and validity of the model have been established.[21–23] The initial contact of each foot during landing was defined as the first sample during which VGRFs exceeded 5% of the subject's BW. The dependent variables included bilateral hip flexion, hip abduction, knee flexion, knee varus, and ankle flexion at initial contact and maximum values for hip flexion, knee flexion, ankle flexion, and VGRFs and the time elapsed from initial contact to these maximum values.

Statistical Analysis

Statistical analyses were performed using SPSS software (version 15; SPSS, Chicago, Illinois). For each condition, dependent *t*-tests were applied to detect both bilateral difference and between-condition differences for each variable. Statistical significance was set at $p < 0.05$.

RESULTS

Results are presented in Table I. Between-condition differences were detected in six variables. Under the NV condition, increased hip abduction angle and increased knee flexion angle at initial contact, decreased maximum knee flexion angle, greater maximum VGRF, decreased time to maximum ankle dorsiflexion, and prolonged time to maximum VGRF were detected in one or both legs.

Four variables showed significant bilateral differences. Hip flexion at initial contact, maximum knee flexion, and maximum VGRF were different bilaterally in both conditions, whereas time to maximum ankle dorsiflexion was different bilaterally only under the NV condition.

DISCUSSION

Landing is a common task performed during military training and tactical operations such as exiting a vehicle from height and traversing uneven terrain or obstacles. When necessary, such tasks are performed at night reducing or eliminating

TABLE I. Between-Condition and Bilateral Comparisons of Joint Angles, VGRFs, and Timings

	Left Leg (Mean ± SD)		Between Condition Comparison (*p*-value)	Right Leg (Mean ± SD)		Between Condition Comparison (*p*-value)	Bilateral Comparison (*p*-value)	
	WV	NV		WV	NV		WV	NV
Initial Contact								
Hip Flexion (°)	22.8 ± 7.0	22.6 ± 7.9	0.492	21.4 ± 6.8	21.2 ± 8.0	0.654	**<0.001**	**<0.001**
Hip Abduction (°)	4.0 ± 3.3	4.6 ± 3.6	**0.002**	3.7 ± 3.3	4.2 ± 3.2	**0.003**	0.412	0.361
Knee Flexion (°)	20.0 ± 6.0	20.0 ± 5.7	0.775	18.1 ± 6.2	18.7 ± 5.8	**0.046**	**<0.001**	**0.004**
Knee Varus (°)	3.4 ± 5.7	3.3 ± 5.7	0.597	3.7 ± 5.1	3.8 ± 4.9	0.871	0.500	0.353
Ankle Plantar Flexion (°)	19.8 ± 9.0	20.0 ± 7.7	0.641	19.3 ± 7.9	19.3 ± 7.5	0.725	0.273	0.142
Maximum Values								
Knee Flexion (°)	89.7 ± 19.4	85.8 ± 19.4	**<0.001**	88.6 ± 19.3	85.4 ± 19.5	**<0.001**	0.116	0.529
Ankle Dorsiflexion (°)	26.9 ± 8.0	26.4 ± 6.3	0.439	27.0 ± 7.2	26.6 ± 6.3	0.336	0.904	0.761
VGRF (%BW)	341.9 ± 96.4	359.9 ± 89.4	**<0.001**	376.1 ± 96.7	384.1 ± 88.2	0.085	**<0.001**	**<0.001**
Time to Maximum Values								
Knee Flexion (ms)	240 ± 115	236 ± 113	0.618	234 ± 81	238 ± 120	0.600	0.346	0.807
Ankle Dorsiflexion (ms)	224 ± 79	212 ± 79	**0.017**	224 ± 70	224 ± 88	0.994	0.904	**0.002**
VGRF (ms)	38 ± 13	40 ± 11	**0.012**	39 ± 16	40 ± 8	0.809	0.346	0.716

The bolded values indicate the significant difference of $p < 0.05$.

visual input.[19] Affected visual input was considered the main reason of increased risk of injury during night parachuting,[14] and the same mechanism should apply to any general landing task under a condition of limited vision. The purpose of this study was to investigate how the removal of visual input would affect the lower body kinematics and kinetics of Soldiers performing a landing task using the biomechanical model developed previously.[5–8] The Soldiers in the current study landed with greater bilateral hip abduction angles at initial contact and lower bilateral maximum knee flexion angles when visual input was removed. Additionally, greater knee flexion angle at initial contact for the right leg, greater maximum VGRF for the left leg, greater time lag to maximum ankle dorsiflexion for the left leg, and greater time lag elapsed to maximum VGRF for the left leg were identified when the Soldiers were blindfolded. The observed biomechanical changes may be associated with increased risk of lower body musculoskeletal injuries.

Under the NV condition, Soldiers demonstrated greater hip abduction angles bilaterally. Without a significant difference in the knee varus angle, the greater hip abduction was likely a strategy to expand the base of support in the medial–lateral direction. If the center of mass falls outside of such area, posture is unstable and the risk of fall increases. Therefore, expanding the base of support reduces the risk of fall and is beneficial for maintaining postural stability. Without visual input, it may be possible that Soldiers attempt to drop and land more cautiously, resulting in unconscious increased abduction of the hips thereby widening the base of support. A post hoc analysis was performed and demonstrated greater distance between the ankle joint centers in the medial–lateral direction ($p < 0.001$). Although the base of support between the feet increased by 3.5%, it cannot be determined if such increase had any clinical significance on posture stability.

The VGRF induced by landing impact are transferred up through the ankles, knees, and hips, and require significant eccentric muscle contraction for stabilization and suppression of forces. The VGRF creates external dorsiflexion torque at the ankles and external flexion torques at the knees and hips. The ankle plantar flexors, knee extensors, and hip extensors contract eccentrically to resist the external torques, maintaining the stability of the lower extremity. At the knee joint, the contraction of the quadriceps creates an anterior shear force at the proximal tibia, placing stress at the anterior crucial ligament (ACL).[24] Increased tibial anterior shear force is related to increased knee extension torque.[8] Therefore, reducing VGRF is considered essential for preventing noncontact ACL injuries. Previous work demonstrated that increased ankle plantar flexion angle at initial contact was related to decreased VGRF.[10] In addition, increasing knee flexion angle at initial contact and allowing greater knee flexion throughout the landing are surmised to reduce VGRF.[25,26] In the current study, no significant difference was found between conditions in ankle plantar flexion at initial contact. However, the maximum knee flexion angles were smaller when visual input was not available. That is, Soldiers flexed their knees less throughout the landing under the NV condition, similar to that reported by Santello et al.[16] The current result suggests that removing the visual input may reduce Soldiers' VGRF dissipation. The mechanism leading to this decreased maximum knee flexion is unclear. It may be a cautious move as people tend to reduce the range of movement and move more carefully in the dark. With decreased knee flexion, the center of mass of the body is maintained higher with less vertical fluctuation. The decreased knee flexion may suggest increased joint stiffness, attributed to increased stiffness of muscles surrounding the knee.[27] Increased muscle stiffness is because of increased muscle activation level, indicating the muscles are preloaded and ready to contract.[27] Both the less-perturbated center of mass and increased muscle stiffness may help Soldiers to be more reactive to unexpected events and ready for the next move during tactical operations.

With decreased maximum knee flexion angles, one may expect to see greater VGRF under the NV condition. However, maximum VGRF increased significantly only for the left leg, with an 18% BW average increase. Recent computer model simulation demonstrated that a 12% BW increase in VGRF resulted in a 9% BW increase in ACL force.[28] The mechanism behind such an asymmetric change in VGRF is unclear. Bilateral comparisons have not been addressed in previous studies investigating visual input during drop landing because only unilateral data were collected.[15–18] Although the two-legged drop landing task is instructed to be symmetrical activity, asymmetric kinematic and force patterns were found in the current study. For both the WV and NV conditions, the hips and knees were more extended resulting in a straightened right leg. A straightened right leg suggests less energy dissipation following the impact. In addition, the right foot may contact the ground earlier, and therefore assumes greater proportion of load at the initial stage of landing when the left foot has not contacted the ground yet. To verify, a post hoc analysis was performed and found the right foot did contact the ground earlier (6 ms, $p = 0.004$ for WV and 5 ms, $p = 0.015$ for NV). These kinematic asymmetries may partially explain the significantly greater VGRF at the right leg for both the WV and NV conditions. The significant increase in the left leg VGRF under the NV condition suggested decreased bilateral difference in VGRF with vision removed. This raised an interesting question that whether Soldiers dropped in a more symmetric manner without vision. The right knee flexion at initial contact increased significantly when visual input was removed, although the angle was still significantly smaller than the left knee. By flexing the knees more symmetrically, the distribution of impact might be more balanced across the two legs, and the VGRF might be more comparable between each leg, as the Soldiers demonstrated under the NV condition.

In the current study, no bilateral difference or between-condition differences were found in ankle plantar flexion angles at initial contact or maximum ankle dorsiflexion angles. However, WV removed, the time elapse from initial contact to maximum ankle dorsiflexion was shorter for the left leg than the right leg. In addition, this elapsed time for the left leg was shorter under the NV condition. Decreased time elapsed indicates shorter time the ankle joint had for dissipating the VGRF through dorsiflexion. As a result, the loading rate of forces applied on the ankle joint may increase, affecting postural stability and increasing the risk of damage in surrounding tissues. The shorter time reaching maximum dorsiflexion at the left ankle may indicate less eccentric performance of the plantar flexors, limiting the capacity of energy absorption. This may also partially explain the significant increase in the left leg VGRF. However, with the ankle angles unchanged, the current evidence is not sufficient to support that the removal of vision is associated with increased risk of ankle injury.

In summary, the current results suggested some potential mechanisms that theoretically could contribute to the higher risk of injury during night operations in the U.S. Army.[11,13] Without vision, decreased maximum knee flexion was identified, which was potentially because of increased muscle stiffness surrounding the knee joint. Although the increased knee joint stiffness may be protective and can contribute to knee joint stability, it also reduces the knee's capacity of force dissipation. Increased VGRF places greater risk of traumatic joint injuries such as strain, sprain, or ligament rupture. Eccentric muscle activity at the left ankle resisting the external dorsiflexion torque may not be appropriate, resulting in significantly increased VGRF at the left leg. Landing with limited visual input in battlefield would be more dangerous than our standardized, practice-allowed lab testing. The characteristics of terrain are unfamiliar, and Soldiers have to focus on operation conditions instead of the task of landing itself. Plus, subjects did not carry weapons or wear protection gears in the current study. In battlefield, the weight of equipment can further place greater physical demands on Soldiers to perform landing tasks. The increased unpredictability can potentially amplify the differences we found with a relatively more prepared and planned movement. Altered knee kinematics and increased joint moments were found in reactive compared with planned stop-jump tasks.[7] Furthermore, previous studies found increased variability in electromyographic and kinematic patterns during landing without vision.[15,16] These may sum up into a higher chance of inadequate neuromuscular activations when landing at night. Considering the accompanied higher risk of night operation, it may be beneficial to develop training programs in attempt to improve Soldiers' kinematic and neuromuscular performance when vision is affected. It is unclear, however, whether kinematic or muscle activation patterns during landing can be trained to override the lack of visual input. An intervention program conducted on Air Assault Soldiers demonstrated that posture sway in anterior/posterior and medial/lateral directions under no-vision condition can be reduced via balance training with eyes closed.[29] It is also unclear whether such improvements are sustainable. Future research is encouraged to study the design and efficacy of potential training programs with vision deprived. Finally, increased BW or body mass index in military recruits may result in early discharge and higher risk of injury. Increased BW or body mass index in military recruits has been a concern in the U.S. Army. Future research is needed to evaluate whether the potential detrimental effects of the detected biomechanical differences further increase with increased BW.

The current study has its limitations. All subjects performed the WV condition first, practiced before real trials, and were blindfolded for the NV condition after they stepped onto the platform. As the height of the platform remained unchanged in this study, such design raises two potential issues. The first is potential practice effects. In a previous study, Santello et al[16] tested subjects for the NV condition first, varied the platform height, and blindfolded the subjects before stepping onto the platform. No practice effects in kinematics or VGRF were found across trials in either WV or NV condition.[16] Magalhaes and Goroso[30] found the first drop landing trial with vision removed induced prelanding EMG adaptations for the following trials, making muscle activation patterns similar to that observed with vision. However, Santello et al[16] suggested no such adaptation effect for both WV and NV conditions. The second issue is that the subjects were aware of the platform height. Liebermann and Goodman[15,18] allowed their subjects to view the height before dropping and found unchanged or decreased VGRF and earlier muscle firings in rectus femoris before initial contact. Santello et al[16], who detected increased VGRF and no difference in muscle activation timings, argued that viewing the platform height in advance may be used to plan the joint and muscle activation and compensate for the loss of visual input during dropping. Interestingly, our results of decreased maximum knee flexion and increased VGRF were comparable to Santello et al,[16] whereas our design was more similar to Liebermann and Goodman.[15,18] Thus, the current results do not support Santello's argument that viewing the platform height is sufficient to compensate the removal of visual input. It is more likely that even with some visual information gathered before dropping, the loss of vision still overrides an existing movement plan.

This research is among few studies investigating the effect of visual input on biomechanics of landing and was the only study recruiting subjects from military populations. We expect that the results of this study will provide insights for improving Soldiers' training and injury prevention.

CONCLUSION

Nighttime operations are known of greater risk of injury than daytime. The removal of vision alters Soldiers' landing kinematics and GRFs, potentially placing them under higher risk. Physical training to compensate for night-specific tasks is needed for Soldiers to establish a motor program of proper landing skills, and therefore reduce the effect of limited visual input.

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