Journal of Athletic Training 2017;52(11):000–000
doi: 10.4085/1062-6050-52.11.25

www.natajournals.org

original research

Landing Kinematics and Kinetics at the Knee During Different Landing Tasks

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Context: Several tasks have been used to examine landing biomechanics for evaluation and rehabilitation, especially as related to anterior cruciate ligament injuries. However, comparing results among studies in which different tasks were used can be difficult, and it is unclear which task may be most appropriate.

Objective: To compare lower extremity biomechanics across 5 commonly used landing tasks.

Design: Descriptive laboratory study.

Setting: University-operated US Air Force Special Operations Forces human performance research laboratory.

Patients or Other Participants: A total of 65 US Air Force Special Tactics Operators (age = 27.7 ± 5.0 years, height = 176.5 ± 5.7 cm, mass = 83.1 ± 9.1 kg).

Intervention(s): Kinematic and kinetic analysis of double- and single-legged drop landing, double- and single-legged stop jump, and forward jump to single-legged landing.

Main Outcome Measure(s): Hip-, knee-, and ankle-joint kinematics; knee-joint forces and moments; and ground reaction forces (GRFs) were the dependent measures. We used repeated-measures analyses of variance or Friedman tests, as appropriate, to assess within-subject differences across tasks.

Results: Peak vertical GRF and peak knee-flexion angle were different among all tasks ($P < .001$). Single-legged landings generated higher vertical GRF ($\chi^2 = 244.68$, $P < .001$) and lower peak knee-flexion values ($F_{4,64} = 209.33$, $P < .001$) except for forward jump to single-legged landing, which had the lowest peak knee-flexion value and the second highest peak vertical GRF. The single-legged drop landing generated the highest vertical ($\chi^2 = 244.68$, $P < .001$) and posterior ($\chi^2 = 164.46$, $P < .001$) GRFs. Peak knee-valgus moment was higher during the double-legged drop landing ($\chi^2 = 239.63$, $P < .001$) but similar for all others.

Conclusions: Different landing tasks elicited different biomechanical responses, no single task was best for assessing a wide range of biomechanical variables related to anterior cruciate ligament injuries. Therefore, depending on the goals of the study, using multiple assessment tasks should be considered.

Key Words: landing biomechanics, stop jump, drop landing, military athletes

Key Points

- Different landing tasks elicited different demands and, thus, different landing characteristics.
- Researchers and clinicians should consider using biomechanical evaluations of tasks that are relevant to particular situations.
- When comparing studies or clinical observations in which different landing tasks are used, caution is needed.
- Using multiple assessment tasks may provide a better representation of performance or predicted injury risk while the athlete participates in a certain sport or activity.

Athletic trainers are in a unique position in having the capability and responsibility to design and implement group-specific or individualized programs for preventing athletic injuries. Hootman et al[1] reported that approximately 53% of all injuries sustained in National Collegiate Athletic Association sports were to the lower extremity, and up to 36.8% of injuries were classified as noncontact and potentially preventable. Similarly, Sell et al[2] noted that 62.6% of injuries sustained by active-duty military personnel affected the lower extremity, and 63.7% of all injuries occurred during training or recreational or sport activities. Similar lower extremity injury profiles have also been observed in Special Operations Forces.[3,4] Many researchers[5–10] have investigated landing characteristics for injury prevention and rehabilitation due to higher incidence rates of lower extremity injuries and the potential for prevention by modifying landing biomechanics.

Musculoskeletal injuries to the lower extremity are among the most frequent sport-related injuries and are common in military forces.[1,11,12] Researchers[6,8,10,13–16] have typically measured biomechanical characteristics during landing tasks to assess the risk for musculoskeletal injury and examine potential prevention strategies. In the injury-prevention literature, many protocols have been used to

Table. Comparison of Landing Characteristics by Task Extended on Next Page

	Landing Task					
	Double-Legged Drop Landing			Double-Legged Stop Jump		
Landing Characteristic	Mean ± SD[a]	IQR[b]	Median[b]	Mean ± SD[a]	IQR[b]	Median[b]
Peak vertical ground reaction force, % body weight	360.14 ± 116.98	173.10	341.99	190.07 ± 57.06	85.36	180.06
Peak posterior ground reaction force, % body weight	46.39 ± 35.41	20.49	31.68	25.13 ± 15.59	15.57	18.42
Hip flexion at initial contact, °	21.55 ± 7.76	10.70	20.65	49.49 ± 10.79	17.55	50.03
Hip abduction at initial contact, °	1.35 ± 5.24	7.10	1.52	2.55 ± 5.55	7.46	3.05
Knee flexion at initial contact, °	21.63 ± 7.94	9.86	20.02	32.22 ± 10.68	16.36	32.40
Knee varus at initial contact, °	6.03 ± 5.40	8.46	6.11	11.14 ± 7.03	10.48	9.96
Ankle plantar flexion at initial contact, °	21.25 ± 8.39	7.77	21.15	7.91 ± 14.85	27.83	9.85
Peak hip flexion, °	61.40 ± 19.34	30.16	61.21	78.18 ± 11.35	15.16	78.54
Peak hip adduction, °	0.25 ± 5.99	6.88	−0.55	−0.92 ± 5.76	8.17	−1.19
Peak hip abduction, °	4.09 ± 6.27	7.03	4.32	5.49 ± 6.02	9.33	5.74
Peak knee flexion, °	91.50 ± 16.44	21.70	91.30	101.53 ± 13.68	20.27	101.67
Time to peak knee flexion, °	0.23 ± 0.07	0.09	0.22	0.24 ± 0.06	0.06	0.24
Peak knee varus, °	−5.23 ± 6.20	8.97	−4.90	−10.12 ± 7.83	10.48	−9.26
Peak knee-abduction moment, Nm/kg	0.87 ± 0.54	0.91	0.82	0.45 ± 0.25	0.31	0.45
Peak proximal anterior tibial shear force, N/kg	10.21 ± 1.75	2.26	10.12	7.58 ± 1.73	1.84	6.97

Abbreviation: IQR, interquartile range.

[a] Reported for normally distributed variables.

[b] Reported for variables that were not normally distributed.

[c] Reported for analyses that were not normally distributed (Friedman test).

[d] Non-normally distributed (Friedman test).

[e] Normally distributed.

assess the biomechanical characteristics of landing, but the differences in characteristics elicited by the various tasks are unknown. Most commonly, investigators have used tasks that involved either landing from a standardized height (drop landing)[2,7,8,14,17,18] or a landing countermovement jump, such as the stop jump.[2,10,16,19] These tasks have been performed using both a double- and a single-legged method.[9,17,19] Whereas they may all be valid methods for examining landing biomechanics, biomechanical characteristics, such as peak vertical ground reaction force (GRF), maximum knee flexion, maximum knee valgus, and maximum knee loading, are likely influenced by the variances among these tasks and we need to demonstrate if differences exist.

Dynamic postural stability is also thought to be an important component for assessing injury risk and rehabilitation and, therefore, is important to measure along with landing biomechanics.[20,21] Authors[22,23] have described various tasks to measure dynamic postural stability, but a commonly used task is a double-legged forward jump to a single-legged landing. Givena similar task used to measure lower extremity landing characteristics and dynamic postural stability, it is possible that both components can be measured concurrently, thereby increasing the efficiency of testing.

Athletic trainers and human performance staff in the military setting are often faced with the challenge of developing injury-prevention programs based on the most current evidence. However, researchers[6,13,16,18,19] investigating risk factors for knee injuries have used different strategies to evaluate the biomechanical characteristics of landing, which may have influenced their findings. We must first determine if common biomechanical characteristics reported at the knee are similar among tasks before appropriate comparisons can be made among studies in which different landing tasks were used. Therefore, the purpose of our study was to determine if different biomechanical tasks elicited different landing characteristics. We hypothesized that hip, knee, and ankle kinematics at initial contact would remain similar; peak kinematic values, peak GRF, external knee-valgus moment, and proximal anterior tibial shear force would differ between drop-landing and stop-jump tasks; and single-legged tasks would elicit the highest knee-joint loading. We also aimed to compare a forward jump to single-legged landing (FJSL) task with these other landing tasks and hypothesized that the FJSL would elicit landing characteristics similar to other single-legged landing tasks. The results of this study will establish differences or similarities in the landing characteristics elicited by each task and inform researchers and clinicians about which tasks may be more appropriate for assessing specific characteristics and what may be comparable among landing tasks.

METHODS

Participants

A total of 65 US Air Force Special Tactics Operators (age = 27.7 ± 5.0 years, height = 176.5 ± 5.7 cm, mass = 83.1 ± 9.1 kg) were recruited to participate as part of a large-scale injury-prevention and performance-enhancement project. All participants self-reported being free of injury and medically cleared for full active duty at the time of the study. The volunteers were right-limb dominant; the *dominant limb* was defined as the lower limb preferred for kicking. All participants provided written informed consent, and the study was approved by the Institutional Review Board of the University of Pittsburgh and the United States Air Force.

Table. Extended From Previous Page

Landing Task											
Forward Jump to Single-Legged Landing			Single-Legged Drop Landing			Single-Legged Stop Jump			Analysis of Variance		
Mean[a]	IQR[b]	Median[b]	Mean ± SD[a]	IQR[b]	Median[b]	Mean ± SD[a]	IQR[b]	Median[b]	*F* Value[a]	χ^2 Value[c]	*P* Value
435.96 ± 100.66	125.95	435.87	488.99 ± 101.20	120.80	504.02	293.21 ± 62.75	84.68	287.23	[d]	244.68	<.001
46.52 ± 31.75	31.75	35.00	61.61 ± 36.21	31.18	50.36	35.46 ± 25.50	23.85	24.97	[d]	164.46	<.001
31.73 ± 9.10	11.00	30.20	20.11 ± 7.38	9.11	19.52	39.37 ± 9.14	11.94	38.88	[d]	264.88	<.001
9.45 ± 6.21	8.24	8.97	8.03 ± 6.53	9.94	8.22	5.39 ± 7.23	11.46	4.35	82.12	[e]	<.001
15.10 ± 7.09	9.46	14.11	14.91 ± 6.54	9.53	14.37	20.21 ± 7.30	9.38	21.28	148.90	[e]	<.001
4.90 ± 4.17	5.87	5.01	3.28 ± 4.59	6.80	3.69	5.67 ± 5.38	7.01	5.16	71.31	[e]	<.001
22.53 ± 12.65	11.61	26.02	27.64 ± 6.55	7.65	27.24	12.83 ± 15.52	28.51	17.10	[d]	115.63	<.001
45.25 ± 11.17	16.01	44.20	43.23 ± 11.69	17.06	40.97	60.26 ± 10.44	14.42	59.81	146.36	[e]	<.001
2.76 ± 7.01	7.61	2.10	5.91 ± 7.12	10.39	6.44	8.73 ± 7.21	10.20	7.77	[d]	144.64	<.001
9.56 ± 6.25	8.09	9.27	8.35 ± 6.59	9.38	8.30	5.51 ± 7.22	11.54	4.35	[d]	164.41	<.001
57.76 ± 10.33	13.37	57.54	68.93 ± 11.49	12.81	67.75	73.59 ± 9.87	11.84	74.41	209.33	[e]	<.001
0.18 ± 0.06	0.07	0.16	0.23 ± 0.07	0.07	0.21	0.26 ± 0.07	0.10	0.26	[d]	54.20	<.001
−4.32 ± 4.60	6.16	−4.77	−2.29 ± 5.67	7.18	−3.16	−4.99 ± 6.01	7.90	−4.62	55.78	[e]	<.001
0.54 ± 0.47	0.57	0.43	0.59 ± 0.39	0.52	0.47	0.51 ± 0.33	0.40	0.42	[d]	239.63	<.001
10.57 ± 2.44	3.00	10.93	12.10 ± 1.77	2.75	12.06	9.44 ± 1.90	2.01	9.39	[d]	175.06	<.001

Instrumentation

Three-dimensional hip, knee, and ankle kinematic and kinetic data were quantified using a camera-based motion-analysis system with an integrated dual force-plate system. The motion-capture system (Vicon Motion Systems, Centennial, CO) consisted of 8 infrared cameras that collected retroreflective marker trajectory data at a frame rate of 200 Hz. Retroreflective markers were placed on specific anatomic landmarks (bilateral anterior-superior iliac spine, posterior-superior iliac spine, lateral thigh, lateral femoral epicondyle, lateral shank, lateral malleolus, posterior heel, and head of the second metatarsal), and anthropometric measurements (body weight, height, lower extremity length, and knee- and ankle-joint widths) were recorded and used in the biomechanical model. We used force platforms (model 9286BA; Kistler Instrument Corp, Novi, MI) to collect 3-dimensional GRF data at a sampling rate of 1200 Hz.

Procedures

All participants completed 3 practice trials and 3 successful test trials of each landing task in the order of FJSL,[22] double-legged stop jump (DLSJ),[16] single-legged stop jump (SLSJ), double-legged drop landing (DLDL),[2] and single-legged drop landing (SLDL).[24] All tasks were completed in the operators' own athletic footwear and on the dominant limb. The FJSL task was performed with participants standing at 40% of their height away from the edge of the force platform with a 30.5-cm hurdle positioned at 20% of their height. We instructed participants to perform a double-legged jump over the hurdle, land with their dominant limb on the force platform, and maintain balance for 5 seconds. If they did not clear the hurdle, land completely on the force platform, stick the landing, or balance for the full 5 seconds, the trial was repeated.

The DLSJ task began with participants positioned with both feet at 40% of their height away from the edge of the force platforms. We instructed them to perform a double-legged broad jump to the force platforms, land with 1 foot on each platform, and immediately perform a maximal vertical jump. For the SLSJ task, participants began the trial standing on their dominant limb and then jumped forward onto a force platform, landing on the same limb, and immediately performing a maximal vertical jump. Trials were repeated if the participant did not land with both feet completely on the platform, paused between landing and vertical jump, or did not perform a vertical jump.

Participants started the DLDL task by standing at the edge of a 76.2-cm–high platform that was positioned directly behind the force platforms. We instructed them to "drop off" the platform and land on both limbs (1 foot on each force platform). The SLDL task was completed in a similar manner. Participants were instructed to begin the trial while standing on their dominant limb on the edge of a 45.7-cm–high platform and, when instructed, to drop off, landing on their dominant limb. Trials were repeated if they jumped off the platform, did not land completely on the force platforms, or did not "stick" the landing.

Data Reduction

We processed lower- extremity kinematic and kinetic data using Nexus Software (version 1.8.5; Vicon Motion Systems) according to the Plug-In Gait (version 1.9; Vicon Motion Systems) biomechanical model, which is the Vicon version of the conventional gait model and is based on the Newington-Helen Hayes gait model.[25,26] Raw marker-trajectory data were filtered using a Woltring filter routine.[27] Ground reaction force data were not filtered to avoid producing errors in peak GRFs, joint moments, and joint forces calculations. Using an anatomic reference system, the Plug-in Gait model then uses relative Euler rotation angles and inverse dynamics to calculate joint kinematic and kinetic measurements. A custom MATLAB script (version R2014a; The MathWorks Inc, Natick, MA) was used to identify joint angles, forces, and external moments at initial contact, as well as maximum values during landing. The analyzed kinematic variables were hip-flexion, hip-abduction, knee-flexion, and knee-valgus angles; ankle plantar flexion at initial contact; and peak values during landing. Time to peak knee flexion

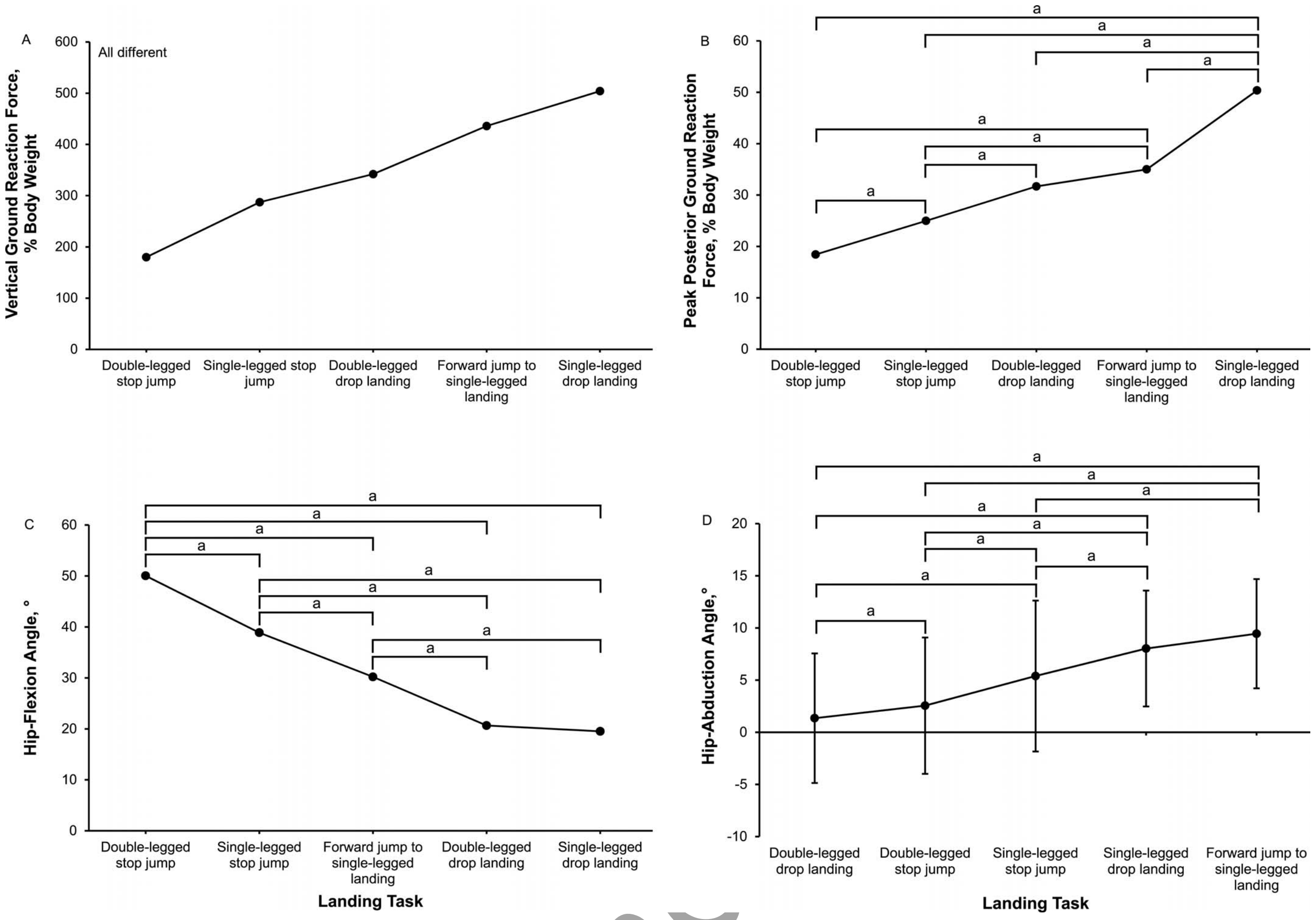


Figure. **Comparison of all measured variables by task (double- and single-legged stop jump, double- and single-legged drop landing, and forward jump to single-legged landing). A, Median peak vertical ground reaction force. B, Median peak posterior ground reaction force. C, Median hip-flexion angle at initial contact. D, Mean hip-abduction angle at initial contact. E, Mean knee-flexion angle at initial contact. F, Mean knee-varus angle at initial contact. G, Median ankle plantar-flexion angle at initial contact. H, Mean peak hip-flexion angle. I, Median peak hip-adduction angle. J, Median peak hip-abduction angle. K, Mean peak knee-flexion angle. L, Median time to peak knee-flexion. M, Mean peak valgus angle. N, Median peak knee-valgus moment. O, Median peak proximal anterior tibial shear force. Tasks are ordered from smallest to greatest value for each variable. Error bars are included when parametric statistical testing was used. [a] Pairwise difference (*P* < .05).**

was calculated from initial contact to peak knee flexion during the landing phase of the task. Kinetic variables that were analyzed consisted of peak vertical and posterior GRFs, peak knee-valgus moment, and peak proximal anterior tibial shear force (PATSF). These values were averaged across the 3 successful trials and used for statistical analysis.

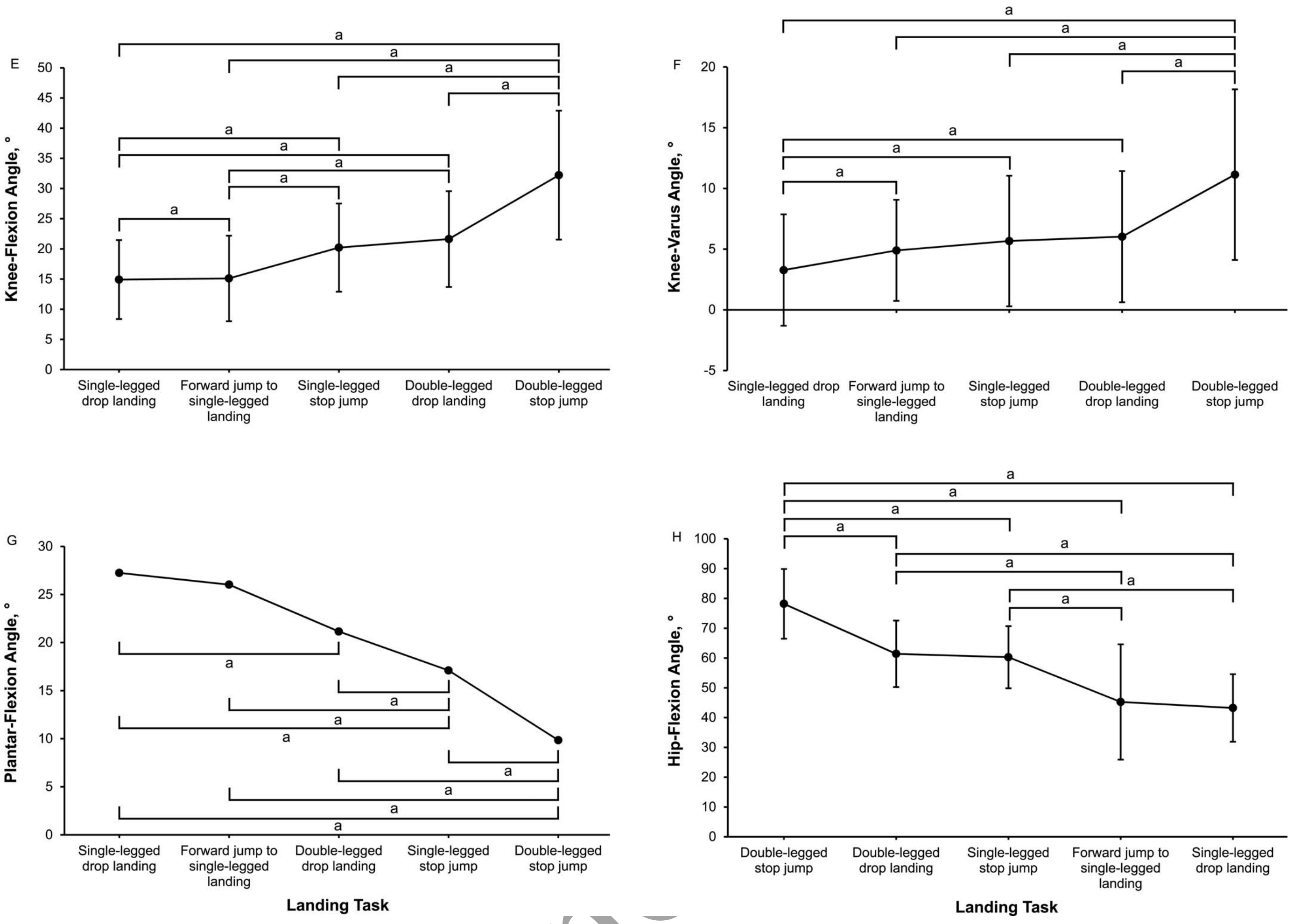
Statistical Analysis

Within-subject differences between tasks were assessed for normality using Shapiro-Wilk tests. Variables that were normally distributed were assessed for differences in kinematic and kinetic variables among tasks using 1-way repeated-measures analyses of variance (ANOVAs). We tested sphericity and made appropriate adjustments to the degrees of freedom if required. If the data were not normally distributed, we used the Friedman test. For post hoc analyses of normally distributed variables, we used *t* tests with pooled variance and Bonferroni adjustments. Post hoc analyses for non-normally distributed variables were completed using the Wilcoxon signed rank test and Bonferroni adjustments ($P < .005$). All statistical analyses were conducted in SPSS (version 21; IBM Corp, Armonk, NY), and the α level was set a priori at .05.

RESULTS

Normality tests showed that peak hip flexion, knee flexion, and knee abduction, along with hip-abduction, knee-flexion, and knee-valgus angles at initial contact, were normally distributed. However, these variables did not meet sphericity requirements; therefore, the Greenhouse-Geiser corrections were used for the repeated-measures ANOVA results. Peak vertical and posterior GRFs, peak knee-abduction moment, peak PATSF, peak hip abduction and adduction, hip flexion and ankle plantar flexion at initial contact, and time to peak knee flexion were not normally distributed; therefore, we used the Friedman test. The ANOVA and Friedman analyses revealed overall within-subject differences among tasks for all measured variables (Table).

Post hoc tests using the Wilcoxon signed rank test with Bonferroni correction showed differences among all tasks for peak vertical GRF. Post hoc tests using paired *t* tests



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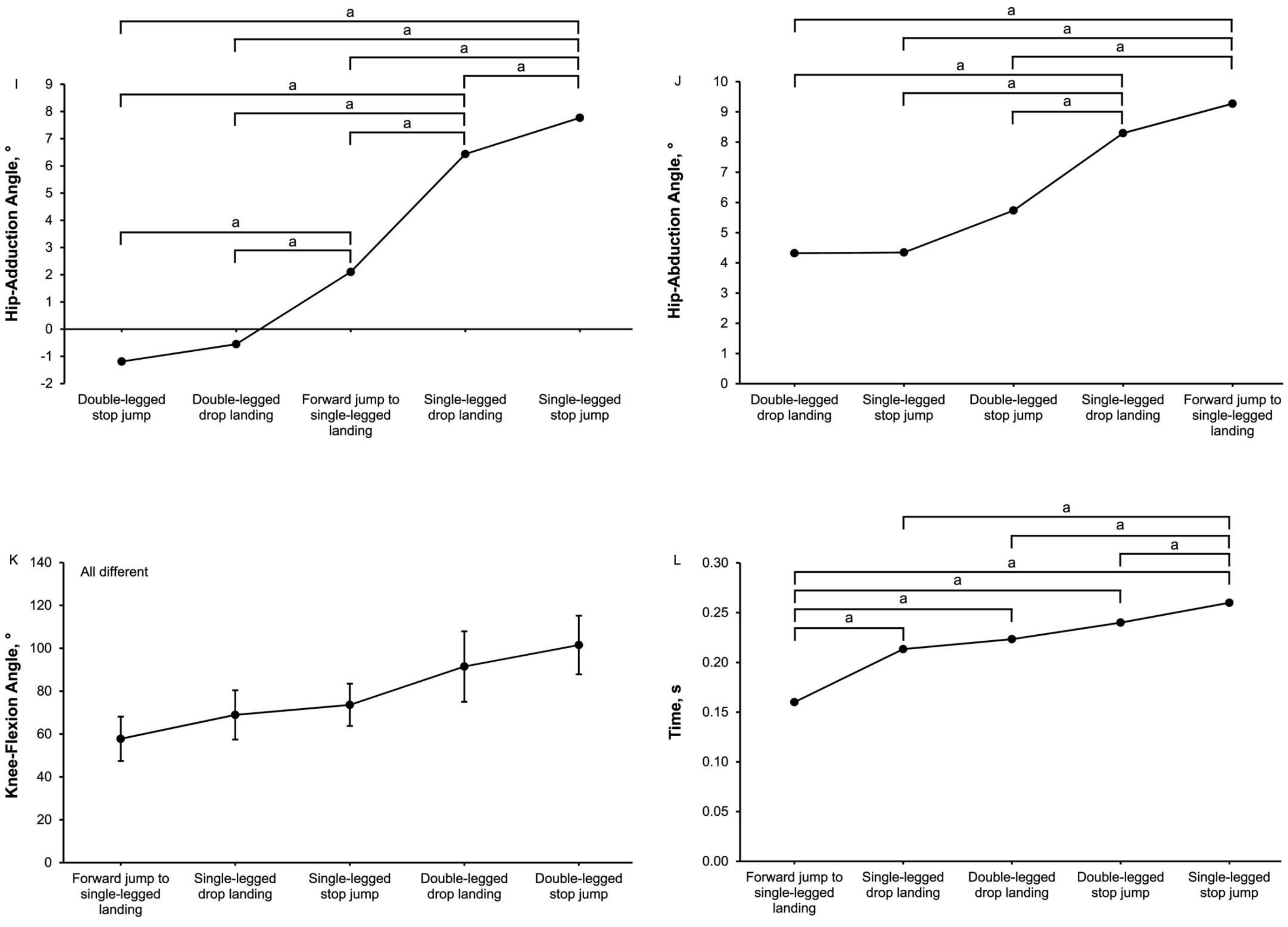
with Bonferroni correction demonstrated differences among all tasks for maximum knee flexion during landing. For all other variables, we observed mixed differences among landing tasks. All post hoc comparisons are presented in the Figure.

DISCUSSION

The purpose of our study was to compare lower extremity kinematic and kinetic measures during 4 common landing tasks and an FJSL task that is often used to assess dynamic postural stability for determining if certain tasks elicited comparable biomechanical characteristics. We hypothesized that landing characteristics at initial contact would remain similar across tasks but would differ between drop-landing and stop-jump tasks and that single-legged landing tasks would elicit higher GRF. We also hypothesized that the FJSL task would elicit landing kinematic and kinetic measures similar to those of other single-legged landing tasks. Our hypotheses were partially supported by our results, which indicated that 1 task alone did not provide comparable biomechanical characteristics across all evaluated lower extremity kinematics and kinetics. Very few similarities were identified among tasks. Furthermore, the FJSL task did not appear to elicit kinematics similar to those of more common biomechanical assessment tasks.

The first aim of this study was to compare landing characteristics between the drop-landing and stop-jump tasks. We observed that drop landings elicited greater vertical and posterior GRFs than stop-jump tasks. Sell et al[2] used a DLDL and a DLSJ task to evaluate landing performance in soldiers. They reported similar vertical GRF values and also demonstrated that drop landings elicited greater vertical GRF values by 150% body weight.[2] However, we did not expect to observe vertical drop landings producing higher posterior GRF values because they do not require the change of direction and horizontal deceleration that the stop-jump tasks require. We suspect that this increase in posterior GRF during the drop landing was likely due to the overall increase in GRFs from the drop height. Participants did use more hip and knee flexion during the SLSJ and DLSJ tasks than during the SLDL and DLDL tasks. This difference in knee- and hip-joint excursion among the different tasks may have decreased the observed peak in GRF by allowing a more gradual absorption of GRF.

The drop-landing task also elicited higher peak PATSF and peak valgus moment. Our results are similar to those of Sell et al,[28] who reported PATSF during a DLSJ task. These authors also demonstrated that peak PATSF was correlated with posterior GRF in healthy active males,[28] and we observed that it was greater during drop landings than



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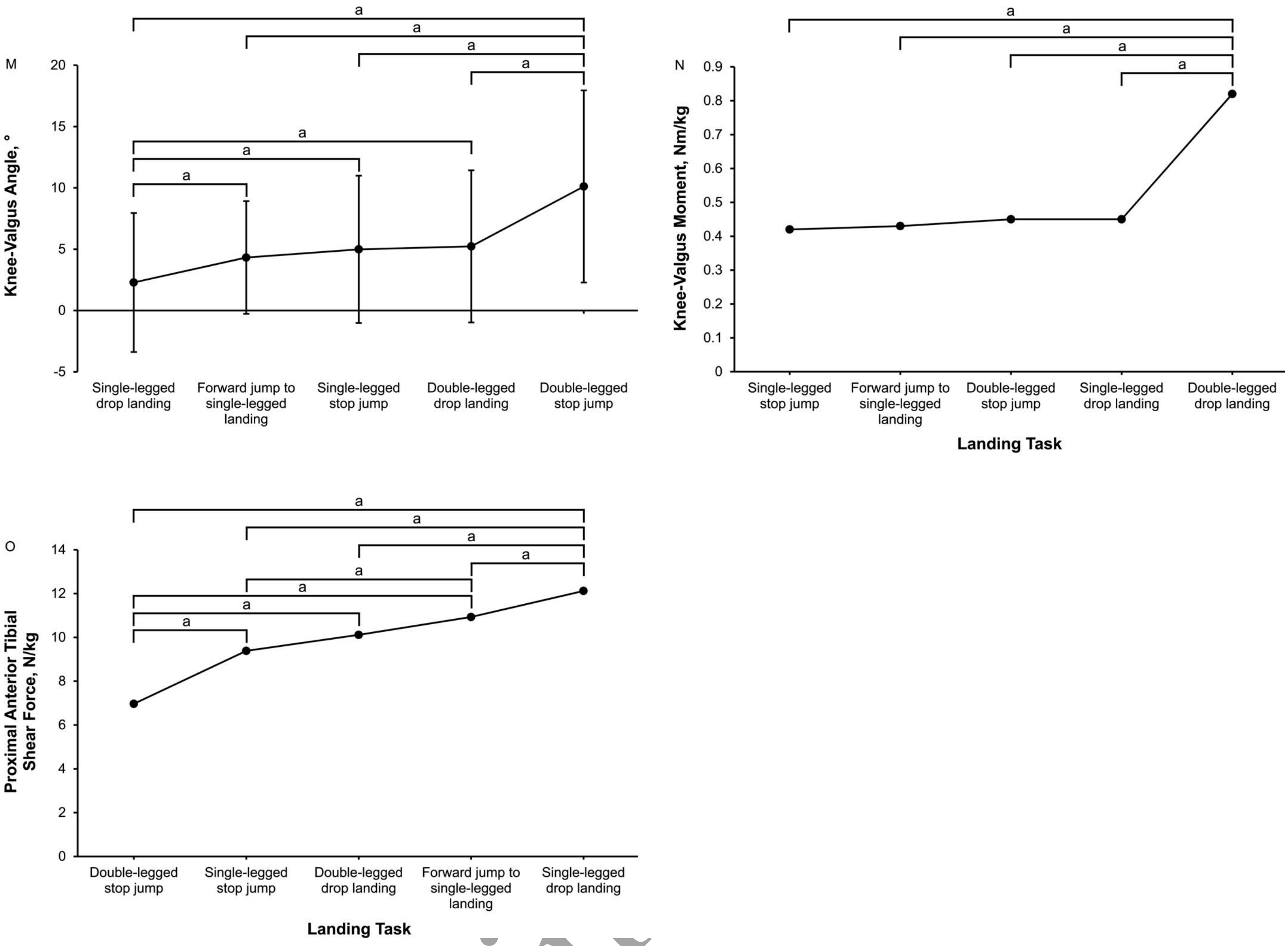
during stop jumps. The increase in knee loading was likely due to decreased peak knee- and hip-joint motion during the drop-landing tasks compared with the stop-jump tasks. In our study, participants used an average of 17.0° more hip flexion and 10.0° more knee flexion during the DLSJ and 17.5° more hip flexion and 5.4° more knee flexion during the SLSJ than during the respective drop-landing tasks. Similarly, Podraza and White[29] found that increased knee flexion during landing decreased vertical GRF, lowered potential knee-joint loading and offered an explanation for increased joint loading during drop-landing tasks compared with stop jumps in healthy active males.

The second aim of our study was to compare characteristics between single- and double-legged landings of the same task. As expected, single-legged landing tasks elicited greater vertical and posterior GRFs regardless of task. We also found that participants used less hip and knee motion during the single-legged landing tasks than during the respective double-legged landing task. Less motion at these joints was likely a cause of the higher GRF values, as less hip and knee motion allows for decreased force absorption during landing. This is also likely a major contributor to the higher peak PATSF seen during the single-legged landings. Sell et al[8] identified differences in lower extremity drop-landing biomechanics by evaluating 2 tasks with different demands in US Army soldiers with and without body armor. The addition of body armor resulted in increased GRF relative to an increase in demand; however, the participants compensated by using greater peak knee flexion.[8] These findings contrast with ours: we demonstrated decreased lower extremity joint motion during the higher demand single-legged landings. This difference may result from single-legged landings creating higher demand than double-legged landings but with less musculature available to absorb these landing forces. The observation of lower knee- and hip-flexion angles at initial contact may suggest that participants rely on static structures to absorb landing forces to compensate for the higher demand.

Third, we compared landing characteristics produced during an FJSL task used to measure dynamic postural stability during more commonly used tasks. To our knowledge, we are the first to examine landing biomechanics during a task intended to measure dynamic postural stability. Our results suggested that the FJSL task elicited different landing strategies than other tasks. Whereas the landing characteristics of the FJSL task most closely reflected those of the drop landing, we observed no distinct patterns between FJSL landing characteristics and any other task.



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LIMITATIONS

Our study had limitations. First, the DLDL and SLDL tasks were performed at different heights. This study is part of a large-scale Warrior Human Performance Research initiative of the US Air Force Special Operations Command, and this drop-landing protocol was chosen and developed based on previous task and demand analyses.[2,30] However, despite the lower drop height for the SLDL, greater peak vertical GRF was observed, demonstrating greater demand than during the double-legged tasks. Second, we evaluated 5 landing tasks that are commonly used in risk-factor studies of lower extremity injury; however, these findings may not be generalizable to other types of biomechanical evaluation tasks that we did not investigate, such as cutting tasks.

CONCLUSIONS

Our results suggested that different landing tasks, although similar, elicited different demands and, thus, different landing characteristics. Researchers and clinicians must consider this when choosing methods to assess landing mechanics, as each task will elicit different landing characteristics. Whereas we assessed within-subject differences among tasks, we still do not know how changing the level of demand, such as jump distance, within the same task may also change landing characteristics. These results also indicated that caution must be used when comparing studies or clinical observations in which different landing-task methods were used. Our findings may also reflect that certain biomechanical evaluations are more relevant in certain situations. For example, SLDLs, similar to single-legged landings performed subsequent to a jumping or leaping activity during a sport or military maneuver, produced the highest peak GRFs and PATSF with the lowest sagittal-plane hip- and knee-joint angles, and seemed to elicit more dependency on ankle plantar flexion during landing. In addition, researchers investigating frontal-plane knee stability or the ability of a training program to limit frontal-plane knee motion or loading will need to select tasks that produce greater knee-valgus moment. We provided evidence that, similar to rebound landings in basketball or landings after stepping off vehicles in the military, the DLDL produced the highest frontal-plane knee motion of the 5 assessed tasks.

Sports and recreational activities require participants to react to and overcome a vast array of demands related to landing and other movement patterns placed on the lower extremity. Using only 1 task is not likely to adequately represent an individual's performance or predicted risk of injury while participating in a given sport or activity. Researchers need to identify a more comprehensive biomechanical evaluation method that can be used to identify risk factors for injury during activities posing different demands.

ACKNOWLEDGMENTS

This study was supported by AFMC/AFRL #FA86501226271.

DISCLAIMER

The opinions expressed herein are solely those of the authors. They do not imply an endorsement by or necessarily reflect the views of the US Air Force or the US Air Force Special Operations Command.

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