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Human Kinetics
TECHNICAL NOTES

Reliability and Validity of Instrumented Soccer Equipment

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Ankle ligament sprains are the most common injury in soccer. The high rate of these injuries demonstrates a need for novel data collection methodologies. Therefore, soccer shoes and shin guards were instrumented with inertial sensors to measure ankle joint kinematics in the field. The purpose of this study was to assess test-retest reliability and concurrent criterion validity of a kinematic assessment using the instrumented soccer equipment. Twelve soccer athletes performed athletic maneuvers in the laboratory and field during 2 sessions. In the laboratory, ankle joint kinematics were simultaneously measured with the instrumented equipment and a conventional motion analysis system. Reliability was assessed using ICC and validity was assessed using correlation coefficients and RMSE. While our design criteria of good test-retest reliability was not supported (ICC > .80), sagittal plane ICCs were mostly fair to good and similar to motion analysis results; and sagittal plane data were valid (r = .90–.98; RMSE < 5°). Frontal and transverse plane data were not valid (r < .562; RMSE > 3°). Our results indicate that the instrumented soccer equipment can be used to measure sagittal plane ankle joint kinematics. Biomechanical studies support the utility of sagittal plane measures for lower extremity injury prevention.

Keywords: biomechanics, kinematics, inertial sensors, magnetic sensors

Soccer is played worldwide by more than 265 million players, with over 24 million players in the United States.[1] Ankle ligament sprains are the most common injury type in soccer,[2,3] and athletes that sustain ankle sprains also suffer from recurrent sprains due to ankle instability,[4,5] incur proprioceptive deficits,[6–8] and are at greater risk of developing ankle osteoarthritis in the future.[9,10] The high rate of ankle injuries and potential for long-term damage demonstrates a need for novel and advanced data collection methodologies that may facilitate the capture of game-like movement.

The laboratory gold standard for collecting human kinematics is a video-based optoelectronic motion analysis system,[11] but inertial-based motion analysis systems are gaining popularity. Optoelectronic systems are typically limited to indoor laboratory environments, cannot be used during athletic competition, and are prone to data loss due to line-of-sight difficulties.[12] Inertial-based motion analysis systems are portable and not limited to small capture volumes. Reliability and validity of inertial sensors measuring ankle joint kinematics have been assessed in studies that employed maneuvers slower than the proposed study and used different statistical analyses. Cloete and Scheffer[13] found highly reliable joint kinematics during gait using the coefficient of multiple determination (CMD) and coefficient of multiple correlations (CMC). CMD and CMC are commonly reported in the literature, but are limited in assessing reliability because correlations do not provide information about the difference between 2 waveform magnitudes, only the level of linear relationship.[14] For this reason, intraclass correlation coefficients (ICCs) are recommended to calculate test-retest reliability of instruments.[15] Validity has been assessed using correlation coefficients[16–18] and CMC[19] with values that ranged from .08 to .98.[16–19] The conflicting results of these studies suggest that more research is needed to investigate the use of such sensors to collect kinematic data. In addition, no studies have attempted to instrument soccer equipment to collect ankle kinematics.

The purpose of this study was to assess reliability and validity of a kinematic assessment using instrumented soccer equipment during athletic maneuvers in the laboratory and field. Design criteria were good test-retest reliability (ICC > .80) and standard error of measurement (SEM) < 5° for plantar flexion/dorsiflexion and < 3° for inversion/eversion; and valid with excellent correlation coefficients (r > .95) and root mean square error (RMSE) < 5° for plantar flexion/dorsiflexion and < 3° for inversion/eversion as compared with a video-based motion analysis system.

Methods

Participants

An a priori power calculation was based on a correlation test used to assess concurrent criterion validity. A total of 12 participants were required using a power of 0.90, alpha of .05, a null hypothesis of $\rho_0 = 0.65$, and an alternative hypothesis of $\rho_1 = 0.95$. Healthy male soccer players were recruited and enrolled in the study (age = 26.3 ± 4.1 y; height = 178.3 ± 7.2 cm; mass = 78.5 ± 7.0 kg). They were recreational soccer athletes and all were right-footed. Inclusion criteria for participants were participation in competitive soccer matches once a week and physical activity for at least 30 minutes, 3 times per week. Participants were excluded if they reported a history of ankle injury or instability, recent (3 months) lower extremity musculoskeletal injury, major ligamentous injury or surgery of the knee or ankle, or concussion or mild head injury within the previous year. Written informed consent approved by the university institutional review board was obtained before participation.

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Instrumentation

Soccer turf shoes and shin guards were instrumented (Figure 1) with the inertial sensors called magnetic field angular rate and gravity (MARG) sensors. The MARG contained a 3D linear accelerometer (± 8 g), 3D angular rate sensor (gyroscope) (± 2000°s^{-1}), and 3D magnetometer (± 8.1 G) to measure sensor orientation at 256 Hz (x-IMU, x-io Technologies Limited, UK). The MARG accuracy was previously assessed with < .8° static RMSE and < 1.7° dynamic RMSE.[20] Ankle joint kinematic data were also collected using a 3D video-based motion analysis system with 8 high-speed cameras at 256 Hz (Vicon Motion Systems, Centennial, CO). Maximum vertical jump height was measured using a Vertec Vertical Jump tester (Sports Imports, Columbus, OH).

Procedures

Participants reported to the laboratory for 2 sessions, 1 week apart to minimize fatigue or memory bias effects.[15] All procedures were performed on day 1, and laboratory and field assessments were repeated on day 2. Participants wore instrumented soccer turf shoes and shin guards for all laboratory and field testing. Equipment on the dominant limb were instrumented and equipment on the other limb were not. Height, mass, leg length, knee width, and ankle width were recorded. Sixteen retro-reflective markers were adhered bilaterally to the lower extremity using the Plug-In Gait (PIG) conventional gait model (Vicon Motion Systems, Centennial, CO).

Participants performed a 5-minute warm-up on a stationary bicycle at a self-selected intensity. Maximum vertical jump height was assessed and used to place the soccer ball height during field maneuvers. The ball was placed at 50% of the participant's maximum vertical jump height.[21] Participants performed 3 athletic maneuvers in the laboratory: drop landing, drop jump, and stop jump (Figure 2). These maneuvers were selected because landing is the most common mechanism of noncontact ankle sprain injuries in soccer athletes.[22–25] Participants performed 2 soccer-specific maneuvers in a climate-controlled indoor practice facility with FieldTurf (Tarkett, Inc., Calhoun, GA). The 2 soccer-specific maneuvers were a jump header and moving header (Figure 2). Three trials of each maneuver were collected with 60 seconds of rest in between trials to prevent fatigue. The landing phase of each maneuver was used for analysis.

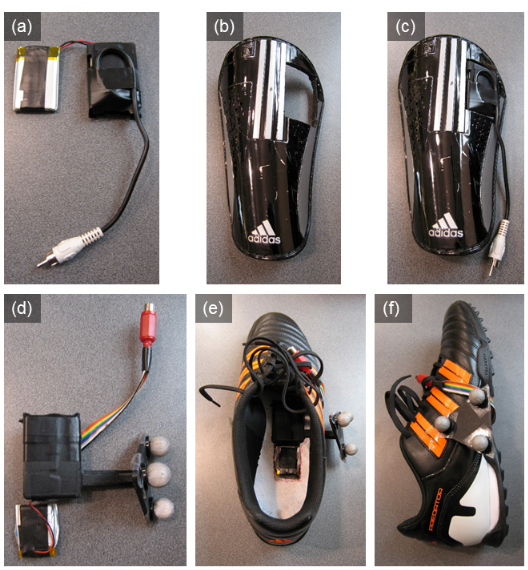

Figure 1 — Instrumented soccer equipment. (a) MARG for shin guard installed in a custom housing with battery and synchronization cable attached. (b) Modified shin guard. (c) Instrumented soccer shin guard. (d) MARG for turf shoe installed in a custom housing with battery and synchronization cable attached. (e–f) Instrumented soccer turf shoe.

Data Reduction

Ankle joint kinematics from the video-based motion analysis system were calculated using the PIG model.[26,27] Ankle joint kinematics from the MARG system were estimated from the orientation of both MARGs using the gradient descent algorithm.[20] After the instrumented soccer equipment were attached to the participant, a static calibration pose was used to determine initial sensor-to-sensor orientation. Three dynamic calibration motions were used to establish orientation matrices to transform from the MARG coordinate system to the segment's anatomical coordinate systems (based on O'Donovan et al[28]). They were: whole body rotation about the longitudinal axis of the test limb to define the vertical anatomical axis for the tibia and foot MARGs; heel lifts to define the joint axis of rotation for the foot; and squats to define the joint axis of rotation for the tibia. Orientation of the foot segment with respect to the tibia segment was used to calculate joint angles from the

Figure 2 — Laboratory and field maneuvers. Phases of the laboratory maneuvers are: (1) the initial position, (2) the intermediate position, and (3) the last position. (a) The drop landing maneuver was a landing from a 40-cm platform. Participants dropped with both feet and landed on the ground with both feet. (b) The drop jump maneuver was the same as the drop landing maneuver except a maximal vertical jump was performed immediately after landing. (c) The stop jump maneuver was a 2-footed jump from 40% of the participant's height to a marked landing location. Immediately after landing with both feet, participants performed a 2-footed vertical jump for maximum height. (d) The jump header maneuver was performed by jumping vertically and striking the ball with the forehead and landing with both feet. (e) The moving header maneuver was performed using a 3 step approach, jumping vertically, striking the ball with the forehead, and landing with both feet.

orientation matrix. Plantar flexion, inversion, and internal rotation angles at initial contact, peak during the landing phase, and overall angular displacement were identified using a custom Matlab script (The MathWorks Inc., Natick, MA). The mean of the 3 trials was used for analysis. MARG and video-based motion analysis data were synchronized using a synchronization pulse (trailing edge of a 1 Hz square wave) generated with a microcontroller.

Initial contact for the instrumented soccer equipment was estimated as the local minimum of foot vertical acceleration that occurred after the ankle began to move into dorsiflexion.[29] Initial contact for the video-based motion analysis system was estimated as the local maximum marker acceleration.[30,31] The algorithm was applied to the heel and toe markers where the local maximum marker acceleration that occurred first was selected as initial contact.

Statistical Analysis

ICCs (2,1) and 95% confidence interval (CI) were used to calculate intersession test-retest reliability[15] and SEM was calculated to obtain an absolute measure of the measurement error in degrees. Concurrent criterion validity of the instrumented soccer equipment was assessed by comparing ankle plantar flexion, inversion, and internal rotation angles measured simultaneously from the MARG and the video-based motion analysis system (using data from day 1). Pearson product-moment correlation coefficients and RMSE were used to quantify differences between MARG and video-based ankle joint kinematics. ICCs were interpreted as poor (< .40), fair to good (.40–.75), and excellent (≥ .75) using Fleiss' criteria.[32] Correlation coefficients were interpreted as moderate (.65–.74), good (.75–.84), very good (.85–.94), and excellent (.95–1.00).[19,33–35] All statistical analyses were performed using SPSS, Version 20 (IBM Corporation, Armonk, NY).

Results

Data from 12 healthy male soccer players were used for analysis. Representative ankle joint kinematics from the instrumented soccer equipment and video-based system during the drop landing maneuver are illustrated in Figure 3. Reliability measures for all planes were mostly fair to good[32] and similar to our PIG results (Tables 1 and 2). Sagittal plane data were highly correlated (r = .900 to .975) for all maneuvers and RMSE was < 5° for drop landing, drop jump, and stop jump maneuvers (Table 3). Frontal plane data were poorly correlated (r = –.074 to .562) for all maneuvers and RMSE was > 3° for all maneuvers, except drop landing (RMSE = 2.86). Transverse plane data were poorly correlated for all maneuvers and RMSE was > 3° for all maneuvers.

Discussion

Ankle ligament sprain injuries are the most common injury type in soccer athletes,[2,3] and measurement of ankle joint kinematics in the field may help to reduce these injuries. The purpose of this study was to assess reliability and validity of a kinematic assessment using

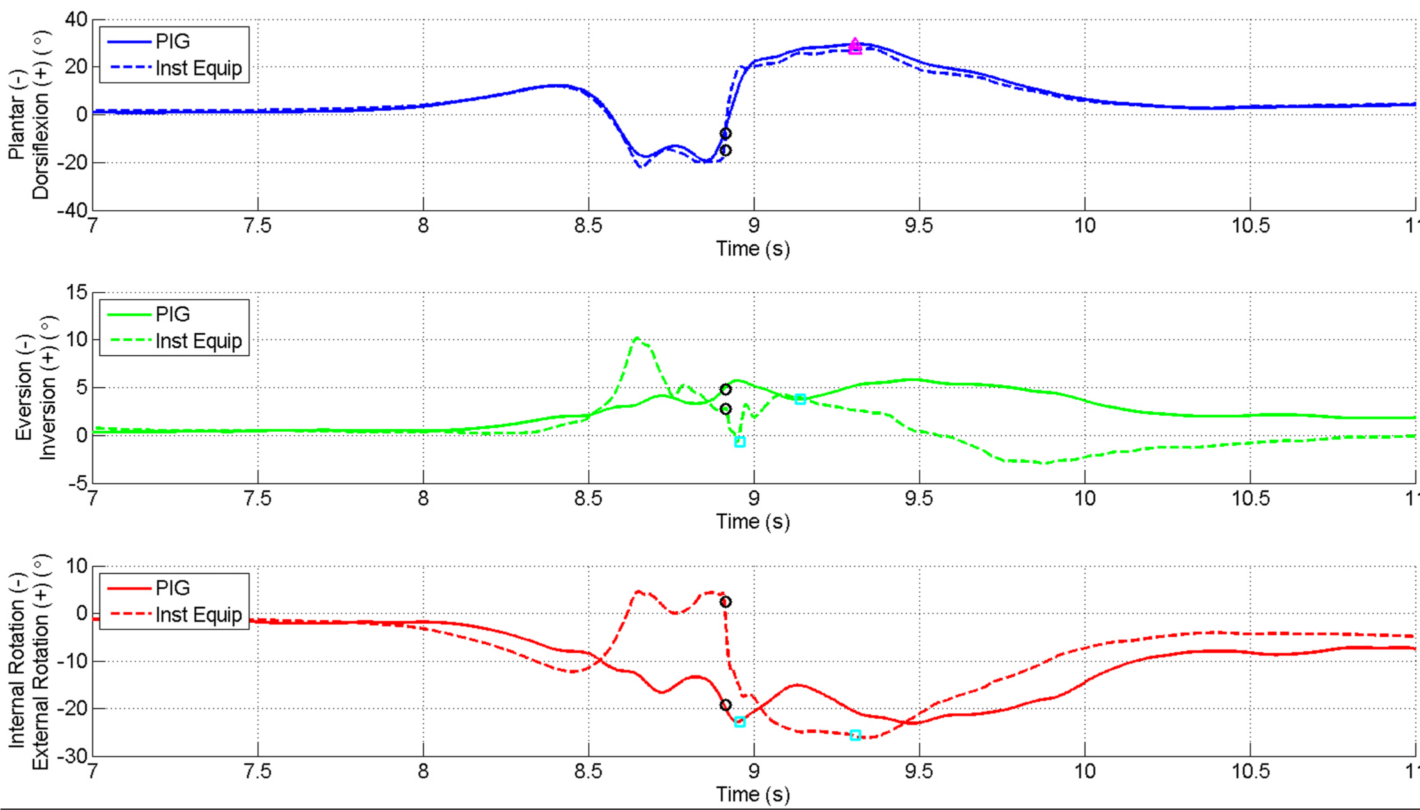

Figure 3 — Ankle joint kinematics of a representative participant from the instrumented soccer equipment (Inst Equip) and video-based system (PIG) during a drop landing maneuver. Circles represent initial contact, triangles represent peak dorsiflexion, and squares represent peak eversion and internal rotation.

Table 1 Reliability statistics for laboratory maneuvers

			Initial Contact (°)				Peak (°)				Time-to-Peak (s)				Displacement (°)			
Task	Method	Variable	ICC	95% CI		SEM	ICC	95% CI		SEM	ICC	95% CI		SEM	ICC	95% CI		SEM
Drop landing	Instrumented equipment	Dorsiflexion	.711	0.266	0.907	2.7	.380	–0.174	0.765	3.9	.693	0.070	0.910	0.051	.518	–0.084	0.835	4.7
		Inversion	.666	0.157	0.892	2.3	.546	0.036	0.840	1.8	.969	0.898	0.991	0.026	.717	0.257	0.910	1.2
		Internal rot.	.761	0.348	0.925	3.3	.761	0.348	0.925	3.3	—	—	—	—	.890	0.667	0.967	3.0
	Plug-in-gait	Dorsiflexion	.743	0.251	0.922	2.8	.822	0.487	0.945	2.2	.899	0.699	0.970	0.028	.809	0.417	0.943	2.9
		Inversion	.812	0.467	0.942	0.9	.674	0.217	0.892	1.7	–.247	0.613	0.310	0.045	.239	–0.384	0.703	1.7
		Internal rot.	.777	0.382	0.931	4.4	.849	0.553	0.954	3.7	.334	–0.311	0.754	0.102	.608	0.092	0.868	3.5
Drop jump	Instrumented equipment	Dorsiflexion	.755	0.354	0.923	2.6	.072	–0.553	0.613	7.3	.733	0.315	0.914	0.037	.084	–0.400	0.584	6.0
		Inversion	.741	0.314	0.918	1.5	.487	–0.033	0.813	2.8	.706	0.239	0.906	0.056	.887	0.629	0.967	1.6
		Internal rot.	.788	0.392	0.935	3.5	.648	0.138	0.885	5.2	.397	–0.124	0.769	0.089	.516	–0.015	0.828	6.9
	Plug-in-gait	Dorsiflexion	.782	0.412	0.932	2.8	.638	0.115	0.882	2.6	.780	0.395	0.931	0.034	.459	–0.048	0.798	5.7
		Inversion	.867	0.607	0.960	0.9	.713	0.273	0.908	1.6	.208	–0.345	0.674	0.103	.397	–0.232	0.783	2.2
		Internal rot.	.837	0.523	0.951	4.3	.596	0.035	0.866	7.7	.059	–0.582	0.609	0.142	.493	–0.121	0.825	6.6
Stop jump	Instrumented equipment	Dorsiflexion	.284	–0.376	0.732	7.1	.251	–0.307	0.698	4.1	.506	–0.002	0.821	0.051	.241	–0.373	0.703	12.7
		Inversion	.058	–0.482	0.584	3.4	.269	–0.301	0.710	3.1	.421	–0.110	0.782	0.103	.438	–0.115	0.794	2.7
		Internal rot.	.558	–0.023	0.851	5.9	.074	–0.550	0.614	11.0	.329	–0.224	0.739	0.151	.136	–0.457	0.642	10.7
	Plug-in-gait	Dorsiflexion	.506	–0.100	0.831	6.4	.398	–0.247	0.785	3.2	.621	0.134	0.872	0.035	.286	–0.306	0.723	11.4
		Inversion	.789	0.409	0.935	0.9	.730	0.319	0.913	1.4	.649	0.182	0.882	0.062	.602	0.107	0.864	1.6
		Internal rot.	.699	0.236	0.903	4.1	.535	–0.009	0.838	6.6	.380	–0.261	0.776	0.140	.605	0.120	0.865	5.5

Note. ICC = intraclass correlation coefficient; CI = confidence interval; SEM = standard error of measurement; Internal rot. = internal rotation.

Table 2 Reliability statistics for field maneuvers

			Initial Contact (°)				Peak (°)				Time-to-Peak (s)				Displacement (°)			
Task	Method	Variable	ICC	95% CI		SEM	ICC	95% CI		SEM	ICC	95% CI		SEM	ICC	95% CI		SEM
Jump header	Instrumented equipment	Dorsiflexion	.535	0.030	0.834	2.2	.145	–0.483	0.654	6.2	.384	–0.245	0.776	0.062	–.155	–0.627	0.425	6.4
		Inversion	.498	–0.013	0.818	4.5	.542	0.037	0.838	4.4	.752	0.332	0.922	0.039	.378	–0.140	0.759	2.1
		Internal rot.	.253	–0.386	0.713	8.4	.265	–0.376	0.719	8.3	.007	–0.547	0.558	0.000	.525	–0.076	0.838	5.2
Moving header	Instrumented equipment	Dorsiflexion	.564	–0.009	0.853	4.7	.648	0.168	0.883	3.6	.642	0.116	0.883	0.020	.563	0.025	0.850	4.1
		Inversion	.767	0.361	0.927	3.3	.305	–0.320	0.737	4.6	.543	–0.015	0.843	0.037	.730	0.295	0.914	3.2
		Internal rot.	–.052	–0.659	0.536	8.3	.660	0.146	0.890	7.1	.881	0.486	0.941	0.015	.674	0.177	0.895	8.0

Note. ICC = intraclass correlation coefficient; CI = confidence interval; SEM = standard error of measurement; Internal rot. = internal rotation.

Table 3 Validity statistics for instrumented equipment (mean ± SD)

Task	Angle	Correlation Coefficient			RMSE		
Drop landing	Plantar / dorsiflexion	.935	±	.072	3.595	±	1.301
	Eversion / inversion	.327	±	.417	2.857	±	1.176
	Internal / external rotation	.545	±	.182	8.358	±	2.821
Drop jump	Plantar / dorsiflexion	.975	±	.015	4.177	±	1.674
	Eversion / inversion	–.074	±	.452	4.759	±	1.170
	Internal / external rotation	.637	±	.170	10.323	±	3.001
Stop jump	Plantar / dorsiflexion	.973	±	.019	4.210	±	1.767
	Eversion / inversion	–.164	±	.415	5.175	±	1.262
	Internal / external rotation	.654	±	.145	10.375	±	3.667

Note. RMSE = root mean square error.

the instrumented soccer equipment during athletic maneuvers in the laboratory and field. We concluded that sagittal plane measurements from the instrumented soccer equipment were accurate, valid, and moderately reliable; frontal and transverse planes were not.

The instrumented soccer equipment performed well in the sagittal plane during athletic maneuvers in the laboratory and field. While our design criteria of good test-retest reliability was not supported, sagittal plane ICCs were mostly fair to good[32] and similar to our PIG results (Tables 1 and 2). Cloete and Scheffer[13] found excellent reliability during gait, a much slower activity than the athletic maneuvers performed in this study. Sagittal plane measurements were also valid and accurate with very good to excellent correlation coefficients ($r > .90$) and low RMSE (< 5.0°). Our results are consistent with the literature where correlation coefficients ranged from .93 to .98[16,18,19] and RMSE ranged from 0.3° to 4.5°.[16,18,28,36] Conversely, Cloete and Scheffer[17] found poor sagittal plane correlations (r = .08 to .17) and RMSE (11.6°) during gait. Frontal and transverse plane measurements with the instrumented soccer equipment were not valid (r = –.22 to .65) or accurate (RMSE > 3.0°), which differs from previous gait studies.[17–19] Overall, sagittal plane measures from the instrumented soccer equipment were accurate, valid, and moderately reliable.

Biomechanical studies support the clinical utility of sagittal plane measures from the instrumented soccer equipment to be used as an injury prevention tool for the ankle[37–39] and knee.[40–42] Brown et al[37] identified that individuals with mechanical ankle instability perform landing tasks using decreased sagittal plane ankle displacement. Decreased sagittal plane ankle displacement was also present during an accidental inversion ankle sprain injury as compared with trials before the injury.[38] Furthermore, a forward dynamic simulation of a side-shuffle movement reported that increased plantar flexion at initial contact increased ankle sprain occurrences.[39] For the knee, decreased sagittal plane ankle displacement during landing is also associated with greater knee valgus displacement[41] and greater peak landing forces,[40,42] both of which are noncontact anterior cruciate ligament injury risk factors. Sagittal plane ankle joint kinematics are easily measured with the instrumented soccer equipment and provide clinically-relevant information to prevent noncontact ankle and knee injuries.

Possible reasons for not finding valid frontal and transverse plane measurements include smaller range of motion during the maneuvers, axis of rotation estimation, and use of the PIG model. Impact accelerations at landing may have introduced error into the orientation estimation algorithm. The algorithm compensates for magnetic field distortion and gyroscope bias drift, but not for the large accelerations experienced during impacts. Future research should investigate alternate orientation estimation algorithms that compensate for large accelerations to improve kinematic measurements of the instrumented soccer equipment—and MARG in general—during high-impact tasks such as the athletic maneuvers performed in this study.

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References

1. The FIFA Big Count 2006: 270 million active in football. Fédération Internationale de Football Association (FIFA) website. http://www.fifa.com/worldfootball/bigcount/index.html. Accessed August 7, 2014.
2. Agel J, Evans T, Dick R, et al. Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train*. 2007;42(2):270–277. PubMed
3. Dick R, Putukian M, Agel J, et al. Descriptive epidemiology of collegiate women's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2002-2003. *J Athl Train*. 2007;42(2):278–285. PubMed
4. Ekstrand J, Gillquist J. Soccer injuries and their mechanisms: a prospective study. *Med Sci Sports Exerc*. 1983;15(3):267–270. PubMed doi:10.1249/00005768-198315030-00014
5. Yeung MS, Chan KM, So C, et al. An epidemiological survey on ankle sprain. *Br J Sports Med*. 1994;28(2):112–116. PubMed doi:10.1136/bjsm.28.2.112
6. Gross MT. Effects of recurrent lateral ankle sprains on active and passive judgments of joint position. *Phys Ther*. 1987;67(10):1505–1509. PubMed
7. Löfvenberg R, Kärrholm J, Sundelin G, et al. Prolonged reaction time in patients with chronic lateral instability of the ankle. *Am J Sports Med*. 1995;23(4):414–417. PubMed doi:10.1177/036354659502300407
8. Ryan L. Mechanical stability, muscle strength and proprioception in the functionally unstable ankle. *Aust J Physiother*. 1994;40:41–47. PubMed doi:10.1016/S0004-9514(14)60453-0

9. Hintermann B, Boss A, Schäfer D. Arthroscopic findings in patients with chronic ankle instability. *Am J Sports Med*. 2002;30(3):402–409. PubMed
10. Valderrabano V, Hintermann B, Horisberger M, et al. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med*. 2006;34(4):612–620. PubMed doi:10.1177/0363546505281813
11. Cuesta-Vargas AI, Galan-Mercant A, Williams JM. The use of inertial sensors system for human motion analysis. *Phys Ther Rev*. 2010;15(6):462–473. PubMed doi:10.1179/1743288X11Y.0000000006
12. Goodvin C, Park EJ, Huang K, et al. Development of a real-time three-dimensional spinal motion measurement system for clinical practice. *Med Biol Eng Comput*. 2006;44(12):1061–1075. PubMed doi:10.1007/s11517-006-0132-3
13. Cloete T, Scheffer C. Repeatability of an off-the-shelf, full body inertial motion capture system during clinical gait analysis. In *Enginering in Medicine and Biology Society* (EMBC), *2010 Annual International Conference of the IEEE*, Buenos Aires, Argentina Aug 31–Sept 4, 2010.
14. Neter J, Wasserman W, Kutner M. *Applied linear statistical models: regression, analysis or variance, and experimental designs*. 2nd ed. Homewood, IL: Irwin; 1985.
15. Portney LG, Watkins MP. *Foundations of clinical research: Applications to practice*. Upper Saddle River, NJ: Prentice Hall; 2000.
16. Bergmann JH, Mayagoitia RE, Smith IC. A portable system for collecting anatomical joint angles during stair ascent: a comparison with an optical tracking device. *Dyn Med*. 2009;8(1):3. PubMed doi:10.1186/1476-5918-8-3
17. Cloete T, Scheffer C. Benchmarking of a full-body inertial motion capture system for clinical gait analysis. In *Enginering in Medicine and Biology Society (EMBC), 2008 Annual International Conference of the IEEE*, Vancouver, British Columbia, Canada Aug 20–25, 2008.
18. Picerno P, Cereatti A, Cappozzo A. Joint kinematics estimate using wearable inertial and magnetic sensing modules. *Gait Posture*. 2008;28(4):588–595. PubMed doi:10.1016/j.gaitpost.2008.04.003
19. Ferrari A, Cutti AG, Garofalo P, et al. First in vivo assessment of "Outwalk": a novel protocol for clinical gait analysis based on inertial and magnetic sensors. *Med Biol Eng Comput*. 2010;48(1):1–15. PubMed doi:10.1007/s11517-009-0544-y
20. Madgwick SOH, Harrison AJL, Vaidyanathan R. Estimation of IMU and MARG orientation using a gradient descent algorithm. In *Rehabilitation Robotics, 2011 Annual International Conference of the IEEE,* Zurich, Switzerland June 29 - July 1 2011.
21. Butler RJ, Willson JD, Fowler D, et al. Gender differences in landing mechanics vary depending on the type of landing. *Clin J Sport Med*. 2013;23(1):52–57. PubMed doi:10.1097/JSM.0b013e318259efa0
22. Arnason A, Gudmundsson A, Dahl H, et al. Soccer injuries in Iceland. *Scand J Med Sci Sports*. 1996;6(1):40–45. PubMed doi:10.1111/j.1600-0838.1996.tb00069.x
23. Cloke DJ, Spencer S, Hodson A, et al. The epidemiology of ankle injuries occurring in English Football Association academies. *Br J Sports Med*. 2009;43(14):1119–1125. PubMed doi:10.1136/bjsm.2008.052050
24. Fousekis K, Tsepis E, Vagenas G. Intrinsic risk factors of noncontact ankle sprains in soccer a prospective study on 100 professional players. *Am J Sports Med*. 2012;40(8):1842–1850. PubMed doi:10.1177/0363546512449602
25. Woods C, Hawkins R, Hulse M, et al. The football association medical research programme: an audit of injuries in professional football: an analysis of ankle sprains. *Br J Sports Med*. 2003;37(3):233–238. PubMed doi:10.1136/bjsm.37.3.233
26. Davis RB, III, Ounpuu S, Tyburski D, et al. A gait analysis data collection and reduction technique. *Hum Mov Sci*. 1991;10(5):575–587. doi:10.1016/0167-9457(91)90046-Z
27. Kadaba MP, Ramakrishnan H, Wootten M. Measurement of lower extremity kinematics during level walking. *J Orthop Res*. 1990;8(3):383–392. PubMed doi:10.1002/jor.1100080310
28. O'Donovan KJ, Kamnik R, O'Keeffe DT, et al. An inertial and magnetic sensor based technique for joint angle measurement. *J Biomech*. 2007;40(12):2604–2611. PubMed doi:10.1016/j.jbiomech.2006.12.010
29. Jasiewicz JM, Allum JHJ, Middleton JW, et al. Gait event detection using linear accelerometers or angular velocity transducers in able-bodied and spinal-cord injured individuals. *Gait Posture*. 2006;24(4):502–509. PubMed doi:10.1016/j.gaitpost.2005.12.017
30. Hreljac A, Marshall RN. Algorithms to determine event timing during normal walking using kinematic data. *J Biomech*. 2000;33(6):783–786. PubMed doi:10.1016/S0021-9290(00)00014-2
31. Hreljac A, Stergiou N. Phase determination during normal running using kinematic data. *Med Biol Eng Comput*. 2000;38(5):503–506. PubMed doi:10.1007/BF02345744
32. Fleiss JL. *Design and analysis of clinical experiments*. New York, NY: Wiley; 1985.
33. Garofalo P, Cutti AG, Filippi MV, et al. Inter-operator reliability and prediction bands of a novel protocol to measure the coordinated movements of shoulder-girdle and humerus in clinical settings. *Med Biol Eng Comput*. 2009;47(5):475–486. PubMed doi:10.1007/s11517-009-0454-z
34. Kadaba MP, Ramakrishnan H, Wootten M, et al. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res*. 1989;7(6):849–860. PubMed doi:10.1002/jor.1100070611
35. Yavuzer G, Oken O, Elhan A, et al. Repeatability of lower limb three-dimensional kinematics in patients with stroke. *Gait Posture*. 2008;27(1):31–35. PubMed doi:10.1016/j.gaitpost.2006.12.016
36. Young D, D'Orey S, Opperman R, et al. Estimation of lower limb joint angles during walking using extended kalman filtering. In *Proceedings of the 6th World Congress of Biomechanics (WCB 2010)*, Singapore Aug 1–6, 2010.
37. Brown C, Padua D, Marshall SW, et al. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech (Bristol, Avon)*. 2008;23(6):822–831. PubMed doi:10.1016/j.clinbiomech.2008.02.013
38. Fong DT-P, Hong Y, Shima Y, et al. Biomechanics of supination ankle sprain a case report of an accidental injury event in the laboratory. *Am J Sports Med*. 2009;37(4):822–827. PubMed doi:10.1177/0363546508328102
39. Wright IC, Neptune R, van den Bogert AJ, et al. The influence of foot positioning on ankle sprains. *J Biomech*. 2000;33(5):513–519. PubMed doi:10.1016/S0021-9290(99)00218-3
40. Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc*. 1992;24(1):108–115. PubMed doi:10.1249/00005768-199201000-00018
41. Hagins M, Pappas E, Kremenic I, et al. The effect of an inclined landing surface on biomechanical variables during a jumping task. *Clin Biomech (Bristol, Avon)*. 2007;22(9):1030–1036. PubMed doi:10.1016/j.clinbiomech.2007.07.012
42. Kovács I, Tihanyi J, Devita P, et al. Foot placement modifies kinematics and kinetics during drop jumping. *Med Sci Sports Exerc*. 1999;31(5):708–716. PubMed doi:10.1097/00005768-199905000-00014