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Original Article

Rotational and Varus Instability in Chronic Lateral Ankle Instability: *In Vivo* 3D Biomechanical Analysis

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We retrospectively evaluated the altered biomechanics of the talus in 15 adult patients (7 males, 8 females) with chronic lateral ankle instability when the ankle joint moved actively from full dorsiflexion to full plantarflexion under a non-weight bearing condition. CT images were taken for the unstable ankle and the contralateral normal (control) ankle. Three-dimensional surface models of both ankle joints were reconstructed from the CT data, and we used a computer simulation program to compare both ankle motions of inversion/eversion in the coronal plane, plantarflexion/dorsiflexion in the sagittal plane, and internal rotation/external rotation in the axial plane. This evaluation method provides *in vivo*, dynamic, and 3D results of ankle motion. In the ankles with chronic lateral instability and the controls, the average talar rotational movement of inversion (+)/eversion (−) was 19.0° and 15.5° and the internal rotation (+)/external rotation (−) was 30.4° and 20.7°, respectively. Paired *t*-tests revealed significant differences in the amount of inversion (+)/eversion (−) ($p = 0.012$) and internal rotation (+)/external rotation (−) ($p < 0.001$) between unstable and normal ankle joints. The difference of mean rotational movement in internal rotation (9.7°) was greater than that of inversion (3.5°). Rotational instability should be considered when evaluating chronic lateral ankle instability.

Key words: three-dimensional motion analysis, chronic lateral ankle instability, talus, ankle joint

Ankle sprain, the most common type of sports injury, often leads to chronic lateral ankle instability [1,2]. Although conservative treatment can successfully address some acute lateral ankle ligament injuries, the lateral ankle ligaments may heal improperly in an elongated position, causing chronic lateral instability of the ankle [1,3]. Hinterman [4] reported that the ankle joint and its surrounding ligaments represent a complex mechanical structure whose mechanical properties highly depend on ligament integrity. The lateral ankle ligaments play a significant role in maintaining rotational ankle stability, in addition to lateral ankle stability. Valderrabano *et al.* [5] reported that lateral ankle sprains are the main cause of ligamentous post-traumatic ankle osteoarthritis.

The amount of laxity can be clinically assessed by a physical examination with the anterior drawer test and the talar tilt test. However, such tests are experience-dependent and limited by inter-observer differences [6], and they cannot determine the location of the instability. Stress radiography is thus used widely as a

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more objective test to diagnose ankle instability. However, the reliability of this test is controversial [7], and stress radiography is a two-dimensional assessment [8]. Magnetic resonance imaging (MRI) is one of the most reliable methods to evaluate lateral ankle instability, but MRI is static, not dynamic; it does not provide functional results or reveal the amount of instability.

A few *in vitro* studies have investigated altered kinematics in lateral ankle instability [9-11], but cadaveric studies cannot directly assess the kinematics of living subjects. Few studies have performed an *in vivo* 3D analysis of ankles with chronic lateral instability during active ankle motion. We conducted the present study to evaluate the *in vivo* altered biomechanics of the talus in patients with chronic lateral ankle instability during active ankle motion under a non-weight bearing condition using a 3D computerized simulation system. We hypothesized that chronic lateral ankle instability would show altered kinematics of the talus compared to the intact, contralateral control ankle based on the concept that both ankles should have the same kinematics during active full dorsiflexion-plantarflexion motion.

Patients and Methods

This retrospective study was approved by the Institutional Review Board of our institute. We obtained CT images from patients with chronic lateral ankle instability treated at our institution between January 2013 and February 2014. The inclusion criteria were that only one ankle was affected, and the contralateral ankle was normal. The affected ankles met all of the following conditions: (1) history and symptoms of repetitive ankle sprain; (2) anterior talofibular ligament and calcaneofibular ligament tears confirmed by MRI; (3) ≥10° of talar tilt in a varus stress radiologic examination; and (4) absence of all three of the prior conditions in the contralateral normal ankle. Patients with instability of both ankles were excluded from this study; those with stiff ankles and limited range of motion were also excluded. Finally, 15 patients (30 ankles) were enrolled in this study. There were 7 males and 8 females with a mean age of 31.9 years (range 17-58 years).

All patients underwent CT scans of both ankle joints. The CT scans were performed with the patient supine under a non-weight bearing condition in two positions: only active full dorsiflexion, and full plantarflexion rather than inversion (Fig. 1).

CT DICOM images of two positions (LightSpeed Pro 64; Siemens, Erlangen, Germany) were obtained. The scanning parameters were as follows: scan time, 60 sec; scan pitch, 2 mm; tube voltage, 120 kV; tube current, 80-100 mA; and slice thickness, 0.5 mm. The CT images were processed into 3D surface models using a 3D simulation program (Bone Viewer™; Orthree Co., Osaka, Japan). Two bone models were superimposed on the tibia shaft and analyzed with a markerless surface registration using a voxel-based registration technique (Bone Simulator™; Orthree).

We represented the rotation of the ankle using 3D vectors in an anatomical orthogonal reference system modified from the tibiofibula coordinate system of the International Society of Biomechanics [12]. We defined the z-axis as the line passing through the center of the shaft of the tibia, and the reference frame as the plane containing both the most lateral point of the lateral malleolus and the z-axis. The y-axis included in the reference frame was defined as the line perpendicular to the z-axis and connecting the most lateral point of the lateral malleolus. Finally, we defined the x-axis as the common line perpendicular to the y- and z-axes (Fig. 2).

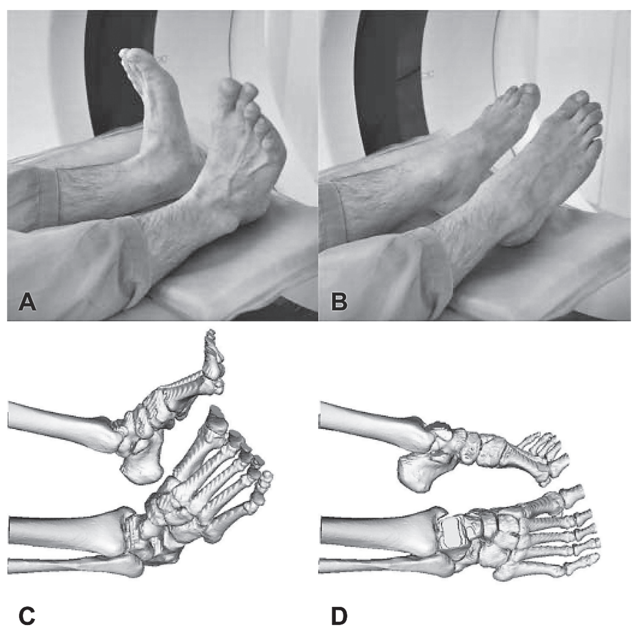

Fig. 1 Image acquisition. CT data were obtained in both ankles including the contralateral normal side in active full dorsiflexion (A) and full plantarflexion (B). The 3D surface model was reconstructed using these CT data (C, D).

We calculated the rotational movement of the talus relative to the tibia in the anatomical coordinate system defined above. Rotational motion of the talus was calculated quantitatively based on Euler space [13]. We quantified the rotation values for inversion (+)/eversion (−) around the x-axis in the coronal plane (y-z), plantarflexion (+)/dorsiflexion (−) around the y-axis in the sagittal plane (x-z), and internal rotation (+)/external rotation (−) around the z-axis in the axial plane (x-y) during full dorsiflexion to full plantarflexion (Fig. 3). Those values imply the amount of rotational movement of the talar joint in each plane.

Paired *t*-tests were used for the statistical analysis, and values of $p < 0.05$ were considered significant. Data were analyzed using IBM SPSS ver. 24.0 (IBM, Armonk, NY, USA).

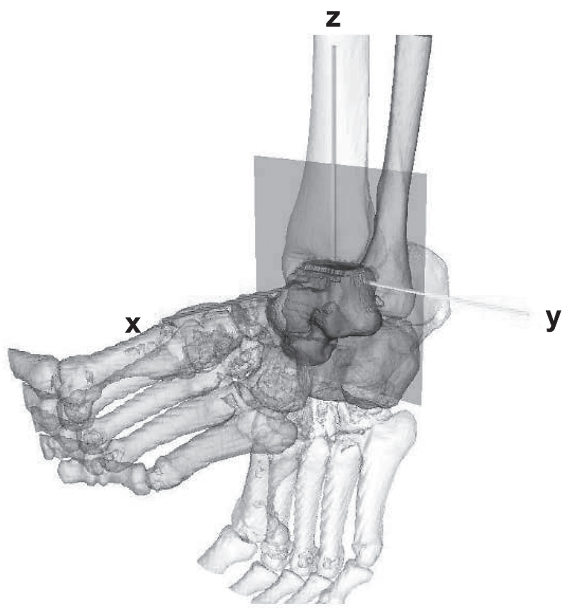

Fig. 2 The anatomical coordinate system. The 3D rotational movement of the talus was calculated based on the coronal (y-z), sagittal (x-z), and axial (x-y) planes in Euler space. The z-axis is the line passing through the center of shaft of the tibia. The reference frame (*gray parallelogram*) is the plane containing both the most lateral point of the lateral malleolus and the z-axis. The y-axis is the line perpendicular to the z-axis and connecting the most lateral point of the lateral malleolus. The x-axis is the common line perpendicular to the y- and z-axes.

Results

In the 15 normal ankle joints, as the ankle moved from dorsiflexion to plantarflexion, the average of the rotational movement was 15.5° for inversion (+)/eversion (−) around the x-axis in the coronal plane (y-z), 54.1° for plantarflexion (+)/dorsiflexion (−) around the y-axis in the sagittal plane (x-z), and 20.7° for internal rotation (+)/external rotation (−) around the z-axis in the axial plane (x-y). In the 15 unstable ankle joints, the average of the rotational movement was 19.0° for inversion (+)/eversion (−) around the x-axis in the coronal plane (y-z), 56.3° for plantarflexion (+)/dorsiflexion (−) around the y-axis in the sagittal plane (x-z), and 30.4° for internal rotation (+)/external (−) around the z-axis in the axial plane (x-y) (Table 1). Paired *t*-tests revealed significant differences in the rotational movement for inversion (+)/eversion (−) ($p = 0.012$) and internal rotation (+)/external rotation (−) ($p < 0.001$) between the unstable and normal ankle joints (Fig. 4). In the unstable ankle joints, a significant increase in the talar rotational movement in internal rotation and inversion was confirmed during ankle motion from dorsiflexion to plantarflexion without weight bearing. The difference in the mean rotational movement in internal rotation in the axial plane (9.7°) was greater than that of inversion

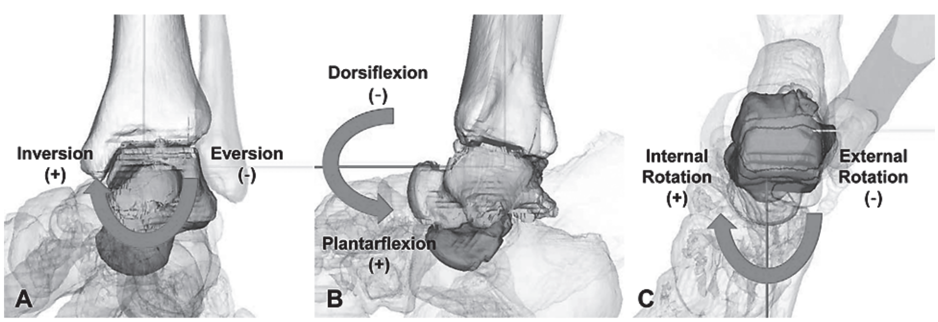

Fig. 3 Three types of rotational movement in Euler angle space. A, Inversion and eversion in the coronal plane (y-z); B, Plantarflexion and dorsiflexion in the sagittal plane (x-z); C, Internal rotation and external rotation in the axial plane (x-y).

Table 1 Three-dimensional rotational movement of the talus

Number	(+): Inversion/(−): Eversion Coronal plane (X-axis)		(+): Plantarflexion/ (−): Dorsiflexion Sagittal plane (Y-axis)		(+): Internal rotation/ (−): External rotation Axial plane (Z-axis)	
	Unstable(°)	Normal(°)	Unstable(°)	Normal(°)	Unstable(°)	Normal(°)
1	14.10	12.80	56.36	50.72	36.12	18.53
2	35.94	21.82	54.84	51.66	26.10	23.55
3	23.83	14.01	60.78	61.48	25.10	18.14
4	13.19	7.12	48.60	55.93	37.93	20.89
5	21.39	22.99	61.72	56.06	26.95	19.55
6	14.33	12.91	49.11	47.35	22.60	13.64
7	22.00	21.23	60.52	56.73	21.53	20.52
8	12.90	9.73	53.83	44.49	31.28	23.72
9	21.01	17.04	64.03	65.79	32.27	16.95
10	13.39	15.86	55.43	53.27	32.13	24.70
11	15.65	19.31	52.77	42.82	26.66	23.70
12	16.66	14.57	57.43	59.75	34.90	15.25
13	17.66	12.66	55.33	57.67	30.26	17.13
14	19.37	13.25	54.55	53.12	36.75	24.36
15	23.76	17.39	59.66	55.27	32.53	29.65
Total*	19.01 ± 6.09	15.51 ± 4.50	56.33 ± 4.44	54.14 ± 6.18	30.41 ± 5.07	20.68 ± 4.27

*Mean ± standard deviation.

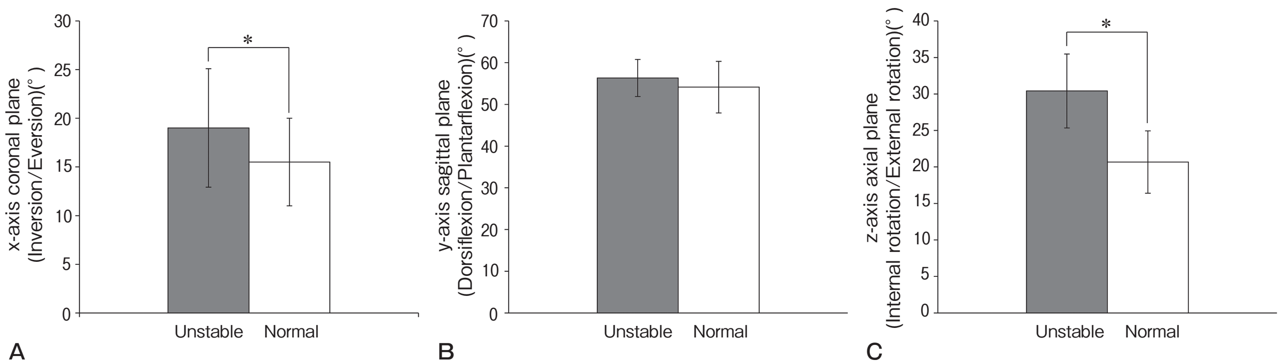

Fig. 4 The 3D rotational movement of the ankle during dorsiflexion and plantarflexion. **A**, Increased inversion in the coronal plane in patients with an unstable ankle; **B**, Slightly increased dorsiflexion in the sagittal plane in patients with an unstable ankle, with no significant difference; **C**, Increased internal rotation in the axial plane in patients with an unstable ankle. $^*p < 0.05$. Shaded box: The unstable group. White box: The normal group. Error bars: standard deviation.

in the coronal plane (3.5°).

Discussion

Most of the clinical evaluation methods used for chronic lateral ankle instability (including the varus tilt test and anterior drawer test) focus on two-dimensional instability. Stress radiography shows a low negative predictive value for the diagnosis of lateral ankle instability even though it yields a high positive predictive value [14]. Raatikainen *et al.* [7] reported that the detection ratio of lateral ankle instability with stress radiographs is approx. 50%. Measurements by plain radiography oversimplify the anatomy of the talus and can lead to inaccurate results [8]. The main drawback of MRI is that it only reveals the anatomical status of the ligaments; it does not provide functional results or the amount of instability. Chandnani *et al.* [15] reported

MRI had 50% sensitivity and 100% specificity for the study of the anterior talofibular ligament and 50% sensitivity and 83% specificity for the study of the calcaneofibular ligament.

In light of the above limitations for the diagnosis of chronic lateral ankle instability, a new evaluation method is needed. A 3D analysis of the ankle joint by CT imaging can be a useful method to evaluate chronic lateral ankle instability. In this study, we used a 3D computerized simulation system with a markerless registration technique to investigate *in vivo* the talocrural joint motion of patients with chronic lateral ankle instability during active full dorsiflexion-plantarflexion motion without weight bearing. This system provides 3D, dynamic, and *in vivo* results of ankle motion.

We hypothesized that the ankles with chronic lateral instability would show increased motion of the talus compared to the intact, contralateral controls. Our analyses revealed that compared to the contralateral controls during ankle motion, the ankles with chronic lateral instability showed increased internal rotation of the talus on the axial plane and inversion of the talus on the coronal plane. Moreover, the difference in the mean rotational movement in internal rotation in the axial plane was greater than that of inversion in the coronal plane.

Kjærsgaard-Anderson *et al.* [16] demonstrated that after the anterior talofibular ligament is ruptured, the amount of transverse-plane motion (internal rotation) of the rearfoot increases by 8-10%. In the present patient series, the talocrural internal rotation was 20.7° in the normal ankle joints and 30.4° in the ankles with chronic instability (Table 1). This result indicates that rotational instability, not varus instability, may be the main instability in chronic lateral ankle instability. Some patients showed low satisfaction scores and experienced several complications after surgical treatment, including recurrent instability in the chronic lateral ankle. This is commonly associated with the selection of a procedure [17] and may be related to restoring rotational instability. Non-anatomical lateral ligament reconstruction techniques such as the Chrisman-Snook, Evans, and modified Watson-Jones procedures restore mainly varus instability, but do not seem to restore rotational instability properly.

Using anterior drawer testing and tilt testing, Colville *et al.* [18] reported that the Evans procedure failed to correct abnormal displacement of the talus and failed to correct internal rotation. Their finding implies that some non-anatomical reconstruction procedures are not sufficient to restore rotational instability. For this reason, surgeons should try to correct not only varus instability but also rotational instability in the treatment of chronic lateral ankle instability.

Other studies using a 3D analysis of the ankle and hindfoot have reported considerable inter-subject variability in the biomechanics of healthy populations [19-24]. In our present analysis, we also observed large variability in the motion of the talus among the 15 patients. Siegler *et al.* [19] reported a high degree of variation in the morphological, architectural, and kinematic properties of the hindfoot among healthy individuals, which derived from natural variations in shape and flexibility. Due to the high level of variability among healthy individuals, previous studies have indicated that the difference in kinematics among subjects might provide a more powerful comparison between groups than the absolute value of the kinematics [19, 21]. However, left-to-right variations in morphological and architectural properties of the hindfoot are small, and small left-to-right variations in the effect of load on architectural properties have also been observed [19]. Siegler *et al.* [19] stated that this high level of symmetry can be exploited in order to establish diagnostic thresholds for pathological conditions, such as chronic lateral ankle instability.

Caputo *et al.* [25] reported that deficiency of the anterior talofibular ligament increases internal rotation, anterior translation, and superior translation of the talus under weight-bearing relative to intact contralateral ankles. Even though their study was conducted *in vivo* using a weight-bearing load without ankle motion, the results also demonstrated that ankles with chronic lateral instability showed increased rotational instability compared to intact, contralateral control ankles, which is consistent with our findings.

Chronic lateral ankle instability involves 3D instability, not just 2D instability. Our analyses demonstrated that ankles with chronic lateral instability had greater internal rotational on the axial plane and inversion on the coronal plane compared to intact, contralateral control ankles. Moreover, the amount of internal rotation was greater than that of inversion. When using this technique, we superimposed the two bone positions to minimize the sum of the squared intensity differences in the segmented voxels. This technique is considered reliable [26,27]. Although 3D analysis using CT has some limitations (such as radiation exposure, high costs, and long procedure time), this technique can yield information that cannot be derived from conventional evaluation methods. This new information will contribute to the proper diagnosis and management of chronic lateral ankle instability.

This study had some limitations. First, it was conducted under a non-weight bearing condition. However, this technique is more physiologic than stress radiography and more functional than MRI. Further studies are needed to investigate altered kinematics and rotational instability of the talus in chronic lateral ankle instability during gait. Second, we investigated only talocrural joint motion, not subtalar joint motion. The changed kinematics of the talus in chronic lateral instability might change the motion of the calcaneus. Further research is necessary to evaluate the kinematic changes of the calcaneus in chronic lateral ankle instability during ankle motion.

Third, we used CT to create a 3D surface model, which has a small risk of radiation hazard. Our protocol required two sets of CT scans, but we used a lower radiation dose than that of routine diagnostic CT. An experimental study showed that the radiation exposure required by this system is 1/30 that of the normal radiation dose associated with a conventional diagnostic CT scan, yet it is associated with similar accuracy [28]. Other investigators have used MRI to investigate the 3D mechanics of the ankle and hindfoot [12,13]. MRI has some advantages, such as the absence of radiation. However, CT has a shorter procedure time and allows for easier bone surface modeling than MRI.

In summary, we compared ankles with chronic lateral instability *in vivo* to intact, contralateral control ankles. We found that, compared to the intact contralateral controls, the rotational movement of the talar joint with chronic lateral ankle instability showed increased internal rotation on the axial plane and inversion on the coronal plane during active full dorsiflexion to full plantarflexion. The difference in the mean rotational movement in internal rotation was greater than that of inversion. Our *in vivo* computerized 3D analysis technique can help diagnose ankles with chronic lateral ankle instability and contribute to our understanding of the biomechanics of these ankles. Rotational instability should be considered when chronic lateral ankle instability is evaluated.

References

1. Hirose K, Murakami G, Minowa T, Kura H and Yamashita T: Lateral ligament injury of the ankle and associated articular cartilage degeneration in the talocrural joint: anatomic study using elderly cadavers. J Orthop Sci (2004) 9: 37–43.
2. Valderrabano V, Hintermann B, Horisberger M and Fung TS: Ligamentous posttraumatic ankle osteoarthritis. Am J Sports Med (2006) 34: 612–620.
3. Gross P and Marti B: Risk of degenerative ankle joint disease in volleyball players: study of former elite athletes. Int J Sports Med (1999) 20: 58–63.
4. Hintermann B: Biomechanics of the unstable ankle joint and clinical implications. Medicine and science in sports and exercise (1999) 31: S459–469.
5. Valderrabano V, Hintermann B, Horisberger M and Fung TS: Ligamentous posttraumatic ankle osteoarthritis. The American journal of sports medicine (2006) 34: 612–620.
6. Fujii T, Luo ZP, Kitaoka HB and An KN: The manual stress test may not be sufficient to differentiate ankle ligament injuries. Clin Biomech (Bristol, Avon) (2000) 15: 619–623.
7. Raatikainen T, Putkonen M and Puranen J: Arthrography, clinical examination, and stress radiograph in the diagnosis of acute injury to the lateral ligaments of the ankle. Am J Sports Med (1992) 20: 2–6.
8. Hoffman E, Paller D, Koruprolu S, Drakos M, Behrens SB, Crisco JJ and DiGiovanni CW: Accuracy of plain radiographs versus 3D analysis of ankle stress test. Foot Ankle Int (2011) 32: 994–999.
9. Bahr R, Pena F, Shine J, Lew WD, Lindquist C, Tyrdal S and Engebretsen L: Mechanics of the anterior drawer and talar tilt tests: a cadaveric study of lateral ligament injuries of the ankle. Acta Orthop Scand (1997) 68: 435–441.
10. Bulucu C, Thomas KA, Halvorson TL and Cook SD: Biomechanical evaluation of the anterior drawer test: the contribution of the lateral ankle ligaments. Foot Ankle (1991) 11: 389–393.
11. Kerkhoffs GM, Blankevoort L, Schreurs AW, Jaspers JE and van Dijk CN: An instrumented, dynamic test for anterior laxity of the ankle joint complex. J Biomech (2002) 35: 1665–1670.
12. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D D'Lima D, Cristofolini L and Witte H: ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. J Biomech (2002) 35: 543–548.
13. Ying N and Kim W: Use of dual Euler angles to quantify the three-dimensional joint motion and its application to the ankle joint complex. J Biomech (2002) 35: 1647–1657.
14. Frost SC and Amendola A: Is stress radiography necessary in the diagnosis of acute or chronic ankle instability? Clin J Sport Med (1999) 9: 40–45.
15. Chandnani VP, Harper MT, Ficke JR, Gagliardi JA, Rolling L, Christensen KP and Hansen MF: Chronic ankle instability: evaluation with MR arthrography, MR imaging, and stress radiography. Radiology (1994) 192: 189–194.
16. Kjærsgaard-Andersen P, Wethelund J-O, Helmig P and Søballé K: The stabilizing effect of the ligamentous structures in the sinus and canalis tarsi on movements in the hindfoot: an experimental study. The American journal of sports medicine (1988) 16: 512–516.
17. Sammarco VJ: Complications of Lateral Ankle Ligament Reconstruction. Clinical Orthopaedics and Related Research® (2001) 391: 123–132.
18. Colville MR, Marder RA and Zarins B: Reconstruction of the lat-

eral ankle ligaments: a biomechanical analysis. The American journal of sports medicine (1992) 20: 594–600.
19. Siegler S, Udupa JK, Ringleb SI, Imhauser CW, Hirsch BE, Odhner D, Saha PK, Okereke E and Roach N: Mechanics of the ankle and subtalar joints revealed through a 3D quasi-static stress MRI technique. J Biomech (2005) 38: 567–578.
20. Imai K, Tokunaga D, Takatori R, Ikoma K, Maki M, Ohkawa H, Ogura A, Tsuji Y, Inoue N and Kubo T: In vivo three-dimensional analysis of hindfoot kinematics. Foot Ankle Int (2009) 30: 1094–1100.
21. Sheehan FT, Seisler AR and Siegel KL: In vivo talocrural and subtalar kinematics: a non-invasive 3D dynamic MRI study. Foot Ankle Int (2007) 28: 323–335.
22. Siegler S, Chen J and Schneck CD: The three-dimensional kinematics and flexibility characteristics of the human ankle and subtalar joints--Part I: Kinematics. J Biomech Eng (1988) 110: 364–373.
23. Beimers L, Tuijthof GJ, Blankevoort L, Jonges R, Maas M and van Dijk CN: In-vivo range of motion of the subtalar joint using computed tomography. J Biomech (2008) 41: 1390–1397.
24. Mattingly B, Talwalkar V, Tylkowski C, Stevens DB, Hardy PA and Pienkowski D: Three-dimensional in vivo motion of adult hind foot bones. J Biomech (2006) 39: 726–733.
25. Caputo AM, Lee JY, Spritzer CE, Easley ME, DeOrio JK, Nunley JA and DeFrate LE: In vivo kinematics of the tibiotalar joint after lateral ankle instability. Am J Sports Med (2009) 37: 2241–2248.
26. Kim E, Moritomo H, Murase T, Masatomi T, Miyake J and Sugamoto K: Three-dimensional analysis of acute plastic bowing deformity of ulna in radial head dislocation or radial shaft fracture using a computerized simulation system. J Shoulder Elbow Surg (2012) 21: 1644–1650.
27. Murase T, Oka K, Moritomo H, Goto A, Yoshikawa H and Sugamoto K: Three-dimensional corrective osteotomy of malunited fractures of the upper extremity with use of a computer simulation system. J Bone Joint Surg Am (2008) 90: 2375–2389.
28. Oka K, Murase T, Moritomo H, Goto A, Sugamoto K and Yoshikawa H: Accuracy analysis of three-dimensional bone surface models of the forearm constructed from multidetector computed tomography data. Int J Med Robot (2009) 5: 452–457.