In Vivo Ankle Kinematics Revealed Through Biplane Radiography: Current Concepts, Recent Literature, and Future Directions

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Abstract

Purpose of Review Lateral ligament repair, specifically the modified Broström-Gould (BG) procedure, has been described for patients with chronic ankle instability (CAI) after failure of nonoperative management. However, there is minimal data about native in vivo ankle bone kinematics and how repairs such as the BG procedure affect the kinematics. The objective of this review is to appraise existing literature that used biplane radiography to measure in vivo kinematics of the ankle in healthy, CAI, and BG populations.

Recent Findings Results showed that the tibiotalar joint contributes more to dorsi/plantarflexion, the subtalar joint contributes more to inversion/eversion and internal/external rotation, and that both joints are capable of complex three-dimensional (3D) motion. Preliminary data suggests that demanding activities (as opposed to walking) are necessary to elicit kinematic differences between healthy and CAI populations. Results also indicate that the BG procedure restores static kinematics and range of motion. All but one of the studies identified in this review collected static, quasi-stance, or partial gait capture data.

Summary The strength of our current knowledge is low given the small sample sizes, exploratory nature of previous work, and lack of rigorous experimental design in previous studies. Future directions include development of an improved protocol for establishing coordinate systems in the ankle bones, continued development of a database of normal kinematics during a variety of activities, and large-scale, longitudinal studies of CAI and BG patients.

Keywords Chronic ankle instability · Broström-Gould · Ankle syndesmosis · In vivo kinematics · Biplanar radiography

Abbreviations

DP	Dorsiflexion/plantar flexion
SP	Supination/pronation
In/Ev	Inversion/eversion
IR/ER	Internal rotation/external rotation
NWB	Non-weight bearing
WB	Weight bearing

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Introduction

In the United States, ankle sprains are the most common lower extremity injuries that present to emergency departments and orthopedic surgeons alike [1–6]. Approximately 2 million ankle sprains occur annually, resulting in 2 billion dollars of healthcare expenditures [7–9]. The majority of ankle sprains are caused by an inversion mechanism that results in an injury to the anterior talofibular ligament (ATFL) (Fig. 1), which can be accompanied by injury to the calcaneofibular ligament (CFL) in more serious injuries [6, 10–12]. Most patients respond successfully to nonoperative treatment [13, 14]. However, up to 40% [15, 16, 17•, 18•] of patients progress to chronic ankle instability (CAI), which has been hypothesized to contribute to premature osteoarthritis of the ankle due to altered joint kinematics [19–23].

Multiple surgical procedures have been described for patients that elect to have surgery after failure of nonoperative management for CAI [25–31]. The modified Broström-

Fig. 1 Lateral ankle anatomy [24]

Gould, which involves anatomic reconstruction of the lateral ligaments, ATFL and CFL, along with mobilization and reattachment of the inferior extensor retinaculum [26, 28], has emerged as the preferred operative treatment [28, 32–34].

There is minimal data about native *in vivo* ankle bone kinematics and how repairs such as the modified Broström-Gould affect the kinematics [35–38]. This lack of data is primarily due to limitations associated with conventional motion analysis systems that require markers to be placed on the skin to identify bony landmarks. Errors result due to poor marker placement leading to inaccurate joint center estimation, and due to movement artifacts associated with relative motion between the skin and the underlying bones (a.k.a skin motion artifact) [39–43]. There are additional challenges specific to the ankle joint complex (AJC), including the inability to place skin-mounted markers on bony landmarks of the intra-articular talus. This makes it difficult to directly measure motion of the tibiotalar joint independent from the subtalar joint [17•, 44•]. Errors in determining ankle joint rotations using skin-mounted markers typically exceed 10° [45], making conventional motion capture inadequate for assessing the effects of injury or surgical repair on ankle kinematics. For these reasons, early *in vivo* studies on ankle kinematics used intracortical bone pins to determine tibiotalar and subtalar kinematics during walking [40, 46]. More recently, biplane radiography (or dual fluoroscopy) has emerged as a promising and less invasive approach for tracking *in vivo* ankle motion [14, 44•, 47, 48]. This approach has demonstrated sub-millimeter and sub-degree precision in tracking ankle bones [49]. Research using this technology has focused on ankle joint

kinematics in static positions [14, 48, 50, 51], at heel strike and toe-off phases of walking [44•], and during running in different types of footwear [47].

The objectives of this review are to appraise existing literature that used biplane radiography or dual fluoroscopy to measure *in vivo* kinematics of the ankle in healthy and CAI populations and to provide perspective for future research directions.

Methods

A literature search was performed on PubMed, Web of Science, and Google Scholar using combinations of the following keywords and their acronyms: lateral ligament stabilization, *in vivo* ankle kinematics, modified Broström-Gould procedure, biomechanical analysis, chronic ankle instability, complications of modified Broström, nonoperative treatment for lateral ligament instability, and surgical treatment of lateral ligament instability. All results from January 2005 through January 2019 were first evaluated by reading the titles and abstracts. If the article met the criterion for the proposed review for biplane radiography, dual fluoroscopy, *in vivo* kinematics of the native ankle, CAI, or following modified Broström-Gould, the full text was accessed and read in its entirety. The bibliography of each manuscript was also reviewed to identify additional manuscripts for potential inclusion in this review.

Biplane Radiography Method

A biplane radiography system (or dual fluoroscopy system) comprises two radiographic source and detector pairs to image the joint. These systems can be constructed using two C-arms [52–54] or from custom-designed components [55, 56]. The two imaging systems typically collect synchronized radiographs of the joint, although asynchronous imaging techniques are under development to eliminate cross-scatter [57]. Images are collected using high-speed cameras optically coupled to the image intensifiers. Three-dimensional subject-specific bone models are generated from CT or MRI and are then registered to the biplane radiographs using an automated or manual registration process to determine bone location and orientation within each pair of synchronized radiographs (Fig. 2). The registration process is repeated for each pair of synchronized radiographs using a manual or semi-automated registration process.

After the registration process is repeated for each bone, the joint motion may be visualized in three-dimensions and joint kinematics (i.e., translations and rotations) may be calculated.

Fig. 2 Overview of the biplane radiography workflow for determining in vivo ankle joint kinematics. **a** The ankle joint is imaged during a dynamic activity such as walking. **b** Synchronized biplane radiographs are collected as the participant passes through the imaging system. **c** Three-dimensional models of the bone of interest are created by segmenting bone tissue from CT or MRI. **d** Coordinate systems are established in each bone to measure relative translation and rotation. **e**

A registration process is carried out by positioning the bone model within the simulated imaging system and a simulated radiograph is generated. The correct position and orientation of the 3D bone model is identified when the simulated radiograph matches the synchronized biplane radiographs. **f** The matching process is repeated for each bone in every pair of synchronized radiographs, resulting in 3D bone position during the entire movement

Review of Literature

Healthy Ankle Kinematics

In 2006, de Asla et al. used the dual-orthogonal imaging technique coupled with 3D magnetic resonance (MR) imaging reconstruction to measure 6 degrees of freedom (DOF)

AJC kinematics (Table 1) [50]. The ankles of five subjects were imaged in non-weight-bearing (NWB) and weight-bearing positions (WB). NWB positions included maximum dorsiflexion-plantarflexion (DP) and maximum supination-pronation (SP). WB positions simulated three phases of the stance phase of gait: heel strike (HS), midstance (MS), and toe off (TO). The main findings were that the tibiotalar joint contributes more to DP, while the subtalar joint contributes more to inversion-eversion and internal-external rotation of the AJC [50]. This small study provided novel insight into in vivo AJC motion during NWB and WB movements.

In 2014, Peltz et al. used dynamic biplane radiography to study the effect of footwear on in vivo ankle kinematics in 12 healthy runners during overground running [47]. The subjects were tested in three footwear conditions: barefoot (BF), an ultraflexible training shoe, and a motion control shoe that limits rearfoot motion in runners who pronate during the ground contact phase. Subjects ran at a self-selected pace along a 15-m long custom elevated platform while radiographic images were acquired at 120 Hz. The study found that tibiotalar motion is greater when running BF compared to with shoes, but there are no differences in subtalar ROM between the three conditions (Table 2).

Koo et al. performed a study on ten healthy subjects walking overground at self-selected pace on an elevated platform [58]. Images were collected during the stance phase. Their results suggested that the terminal dorsiflexion at the tibiocalcaneal joint during stance phase was decomposed into dorsiflexion at the tibiotalar joint and plantarflexion at the subtalar joint. In the beginning phase of terminal stance, dorsiflexion at the tibiocalcaneal joint began to transition to plantarflexion while the joint was still dorsiflexed; this suggested that the subtalar joint initiates plantarflexion motion earlier than the ankle joint.

Campbell et al. [59••] also performed a study on subjects during overground walking; however, they compared BF walking to shod walking and the walking pace was constrained to a foot fall cadence of 90 beats per minute via a metronome. Five participants walked on an elevated 10-m walkway while their right foot landed within the field of view of the biplane fluoroscopy system. They found that peak plantarflexion was significantly higher and neutral dorsiplantarflexion occurred significantly later in the stance phase during BF walking as compared to shod walking. Also, results demonstrated that an eversion peak occurred at the beginning of stance phase during BF walking, whereas an inversion peak was found during shod walking (which occurred significantly earlier compared to the eversion peak in the BF walking).

In 2016, Roach et al. measured ankle kinematics during heel rise and gait [44••]. Ten healthy subjects performed a single-leg heel-rise and walked on the treadmill at 0.5 m/s and 1.0 m/s while being imaged using biplane fluoroscopy. The entire heel-rise activity was imaged; however, for the

Table 1 Demographics and data collection methods for biplane radiography and dual fluoroscopy studies of the AJC

	Population Type	Sample size	Age (years)	Data collection Bone(s) imaged	Activity	No. of trials
de Asla 2006	Healthy subjects	5 (one woman)	32–43	Tibia fibula, talus, calcaneus	Non-weight bearing activity: four complete ROM positions Weight bearing activity: 3 simulated phases of gait (heel strike, midstance, toe off)	7 static positions
Caputo 2009	Unilateral CAI	5 (four women)	19–57	Tibia, talus	25–100% BW on intact ankle and ATFL-deficient ankle	8 static trials; 1 trial per BW condition
Wainright 2012	Unilateral CAI; BG repair	7 (4 women)	37 ± 4	Tibia, talus	25–100% BW on pathologic ankle before and after surgery	8 static trials; 1 trial per BW condition
Peltz 2014	Healthy recreational runners	12 (6 women)	24.2 ± 4.4	Tibia, talus, calcaneus	Running at self-selected pace along a 15 m custom elevated platform in 3 different shoe-wear conditions (barefoot, flexible shoe, and rigid shoes)	3 trials for each footwear condition
Koo 2015	Healthy subjects	10 (no women)	21.5 ± 1.9	Tibia, talus, calcaneus	Overground walking at self-selected pace	1 trial
Campbell 2016	Healthy subjects	5 (no women)	21.5 ± 1.9	Tibia, talus, calcaneus	Overground walking in 2 conditions, barefoot and shod; speed constrained to a foot fall cadence at 90 beats per minute via a metronome	5 trials
Roach 2016	Healthy subjects	10 (5 women)	30.9 ± 7.2	Tibia, talus, calcaneus	Single-leg, balanced heel-rise, and treadmill-walking (0.5 m/s and 1.0 m/s)	2 trials of balanced heel-rise; 2 trials of HS and TO
Roach 2017	Healthy subjects	10 (5 women)	30.9 ± 7.2			
	CAI subjects	4 (3 women)	30.8 ± 4.1			
Anderst 2017	BG repair	8 (7 women)	23 ± 7	Tibia fibula, talus, calcaneus	Repaired and contralateral ankle under two conditions: (1) static, upright standing, (2) overground gait at self-selected speeds	1 trial of static standing; 4 gait trials at self-selected speed

CAI/ chronic ankle instability, BG Broström-Gould

Table 2 Range of motion (ROM) values during gait using biplane radiography or dual fluoroscopy. Values reported represent mean $\pm$ standard deviation unless otherwise noted

	Peltz 2014			de Asla 2006		Koo 2015	Campbell 2016 ^{b,c}		Roach 2016 ^b		Anderst 2017 ^d		
	BF	Free	MC	HS to MS	MS to TO	9% to 86% stance	BF	Shod	0.5 m/s	1.0 m/s	Repaired	Contra	
Tibiotalar angles (°)	D/P	28.2 ± 8.3	15.1 ± 5.9	15.0 ± 6.2	9.1 ± 5.3	4.4 ± 13.0	18.5 ± 3.5	9.1 (5.2, 13.0)	5.7 (3.6, 7.8)	14.9 (12.0, 17.8)	16.3 (13.1, 19.5)	9.2 ± 3.8	8.1 ± 4.0
	In/Ev	2.9 ± 1.3	2.4 ± 0.7	2.6 ± 0.8	-0.1 ± 2.6	-1.7 ± 2.7	5.1 ± 1.1	8.7 (1.9, 15.5)	~4 ^e (NR)	4.6 (2.4, 6.9)	3.8 (2.5, 5.1)	3.7 ± 1.2	3.7 ± 2.2
	IR/ER	7.0 ± 1.4	4.8 ± 2.1	4.3 ± 0.7	3.8 ± 8.2	-1.6 ± 5.9	8.6 ± 3.9	7.5 (0.4, 14.6)	8.1 (4.3, 11.9)	6.9 (4.8, 9.0)	7.4 (4.4, 10.1)	7.2 ± 4.0	7.2 ± 2.8
Subtalar angles (°)	D/P	3.6 ± 1.7	3.5 ± 1.5	3.3 ± 1.3	-0.9 ± 1.2	8.5 ± 2.9	6.6 ± 2.8	NR	NR	7.9 (5.3, 10.4)	8.6 (6.1, 11.1)	3.5 ± 1.5	3.8 ± 1.8
	In/Ev	7.4 ± 3.4	7.9 ± 2.8	7.9 ± 2.6	-1.7 ± 2.7	-10.7 ± 3.8	6.6 ± 4.5	NR	NR	11.6 (8.6, 14.6)	11.3 (9.5, 13.1)	6.1 ± 1.7	7.9 ± 2.5
	IR/ER	4.5 ± 1.8	4.5 ± 1.5	4.6 ± 1.4	-1.5 ± 9.9	12.3 ± 8.3	5.6 ± 2.7	NR	NR	10.7 (6.7, 14.7)	12.5 (9.8, 15.2)	3.3 ± 2.3	2.9 ± 1.5

NR not reported

^a Reported values were determined from three simulated stance phase positions: heelstrike (HS), midstance (MS), and toe-off (TO)^b Results reported as mean (95% confidence interval)^c Gait speed constrained to foot fall cadence at 90 beats per minute via a metronome^d Subjects performed activity at selected pace^e Reported values were estimated from the plot provided

treadmill walking, only the first 20% (heel strike) and last 20% (push off) of the stance phase were imaged as separate trials due to the foot moving on the treadmill and out of the imaging volume during stance. The results overall supported prior in vivo by de Asla et al. [50] that the tibiotalar joint primarily contributes to DP while the subtalar is the primary contributor of In/Ev and IR/ER of the AJC (Table 2). However, the study also showed that subtalar joint contributes to DP and the tibiotalar joint rotates about all three axes. Those results suggested that both joints undergo complex 3D motion during gait. Finally, the study also revealed considerable variability among subjects in tibiotalar and subtalar kinematics [44••].

Pathologic Ankle Kinematics

Caputo et al. studied five individuals with unilateral CAI, specifically with an ATFL injury (ATFL-deficient) [48]. Static images were acquired at loads of 25%, 50%, 75%, and 100% body weight (BW), and the 6 DOF kinematics of the ATFL-deficient ankle were compared with the corresponding contralateral intact ankle at each loading level. They found that ATFL deficiency increased anterior translation and increased internal rotation of the talus in relative to the tibia. There was also a relative increase in the superior translation of the talus on the ATFL-deficient ankle compared to the intact ankle.

Roach et al. followed up their prior baseline study a year later with an exploratory study of patients with CAI using the same methods [17, 44••]. Data was collected on four patients with CAI and ten healthy control subjects during single-leg heel-rise and treadmill walking at 0.5 m/s and 1.0 m/s. Overall, the results showed that the heel-rise activity was more sensitive than walking for identifying differences in kinematics between patients with CAI compared to the healthy control subjects (Table 2). They concluded that weight-bearing activities that require large ROM, balance, and stability may be best for studying kinematic adaptation in patients with CAI. It should be noted that this was an exploratory study given the small sample of CAI patients.

In Vivo Kinematics Following the Modified Broström

Prior studies have suggested that CAI leads to altered kinematics such as increased anterior translation and internal rotation of the talus [17••, 48]. To date, Wainright et al. are the only group to publish the use of dual-orthogonal fluoroscopy to investigate 3D motion of the ankle following the modified Broström procedure for lateral ligament stabilization [14]. Wainright et al. studied seven patients who each underwent modified Broström anatomic reconstruction by a board-certified orthopedic surgeon specializing in foot and ankle surgery. Each ankle was imaged preoperatively. Similar to the Caputo et al. [48], static images were acquired at a desired

loads of 25%, 50%, 75%, and 100% BW by instructing the participant to adjust his or her weight on the contralateral leg. The same methods were performed for each patient 12 months after their respective surgeries. The results showed a significant decrease in anterior translation of the talus in ankles from before to after the repair at 100% BW. A significant decrease was also observed in the internal rotation of talus of the surgically repaired ankles at 75% and 100% BW. The results suggest that the Broström helps to restore normal motion after lateral ankle instability; however, this study was limited to static loading conditions [47, 50].

Our group recently assessed the effects of Broström-Gould repair on ankle kinematics during gait [60]. Both ankles of eight individuals were imaged during gait using biplane radiography after surgery. The origin and insertion sites for the ATFL and CFL were identified on subject-specific bone models obtained from CT to estimate ligament elongation [61]. Two conditions were collected: (1) static, upright standing (one trial per ankle) and (2) gait (four trials per ankle) at a self-selected walking speed. A total of 55 dynamic walking trials were processed for this study, with at least three trials analyzed for each ankle of every subject (Fig. 3).

The results indicated that repaired and contralateral static kinematics were not significantly different (all $p \geq .133$) (Table 2). Similarly, there were no significant ROM differences between repaired and contralateral ankles during the support phase of gait (all $p \geq .072$). Maximum repaired and contralateral ATFL length (14.6 ± 2.0 mm and 13.5 ± 2.5 mm, respectively) and CFL length (24.0 ± 3.3 mm and 25.2 ± 2.5 mm, respectively) were not significantly different (ATFL: $p = 0.117$; CFL: $p = .110$). Side-to-side differences beyond the 95% confidence interval for continuous kinematic curves were observed in at least one of the 12 components of ankle joint rotation for every participant. This study concluded that the modified Broström-Gould procedure appears to restore static kinematics, range of motion during gait, and

maximum ATFL and CFL ligament lengths during the heel-strike to terminal stance phase of gait. However, comparison of continuous joint kinematics between the repaired and contralateral side suggested that the modified Broström-Gould procedure may not restore all components of dynamic rotational ankle kinematics from heel-strike to the terminal stance phase of gait.

Summary and Current Knowledge

Overall, data from these studies indicate that the tibiotalar joint contributes primarily to DP and the subtalar is the primary contributor of In/Ev and IR/ER on the ankle joint. Results also show that both joints undergo more complex movement than previously noted with findings that the subtalar joint contributes considerably to DP and the tibiotalar joint rotates about all three axes. These findings are consistent between NWB and WB activities, specifically walking and running.

For pathological studies, minimal differences were observed between CAI and healthy ankle ROM while walking and running. However, the balanced heel-rise activity exposed more tibiotalar and subtalar variation between the two populations, suggesting that WB activities that require large ROM, balance, and stability may be best for studying kinematics adaptations in the CAI population.

When CAI patients elect to undergo the BG procedure, results indicated that static kinematics, ATFL and CFL length, and ROM during stance phase gait are restored. However, this data also suggests that differences may exist in *continuous* dynamic ankle kinematics following the BG procedure.

While this data contributes to our knowledge of native, CAI, and BG ankle kinematics in vivo, the strength of our current knowledge is low given the small sample sizes and lack of standardized methods across studies.

Fig. 3 Images of the foot during gait at heel strike ($t = 0.0$ s), midstance ($t = 0.35$ s), and terminal stance ($t = 0.70$ s). Kinematic analysis started, on average, 0.02 ± 0.02 s before heel strike, and ended, on average 0.69 ± 0.09 s after heel strike

Future Directions

This review of previous work demonstrates opportunity that exists for increasing our knowledge of in vivo ankle kinematics during functional activities. Suggestions for future research directions include

- *Develop a reliable and automated protocol for establishing coordinate systems on each bone in the ankle.* Due to the absence of external landmarks and the asymmetrical geometry of the bones, it is a challenge to reliably define an anatomic coordinate system on the talus and calcaneus, in particular. Widespread adoption of a method for defining coordinate systems within the ankle joint, and agreement on how to calculate ankle joint kinematics, as exists for most major joints in the human body, will make it easier to compare results across research groups [62, 63].
- *Develop a database of “normal” ankle joint kinematics.* Previous studies that used biplane radiography to measure ankle joint kinematics comprised relatively small groups of participants due to the extensive amount of time required to accurately process biplane radiography data. Large studies of so-called “normal” ankles are needed to serve as a reference for comparison for future studies to evaluate the effects of injury, conservative treatment, and surgical repair on ankle kinematics. Furthermore, the database of normal kinematics should contain sufficient information to classify each participant according to foot type (pes cavus, neutral, pes planus) which will allow sub-analysis of kinematics according to foot type.
- *The rigor of in vivo ankle kinematics studies must improve.* Previous research has typically measured ankle kinematics during only one movement trial for each individual. Multiple movement trials per individual are needed to more accurately characterize their normal kinematics so that kinematics that are truly representative of their typical motion are available. Standardized movements should be identified to provide a reference of comparison across research studies. It is suggested that the contralateral ankle be used as reference for comparison for CAI and post-surgical patients, rather than healthy ankles from other individuals, to account for subject-specific bone morphology which affects AJC kinematics.
- *Ankle kinematics during more strenuous activities and during activities common to athletic competition should be assessed.* Previous research has focused exclusively on the straight-ahead dynamic activities such as walking and running. Future research should focus on movements such as jumping, hopping, lateral hopping, and quick changes in direction that are common to athletic competition.

- *Research should be done to address gaps in knowledge related to the effects of sex, age, and time post-surgery on ankle kinematics.* Due to small sample size in previous studies, the effects of age, sex, and time post-surgery on AJC kinematics have not been investigated.

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Compliance with Ethical Standards

Conflict of Interest Stephen Canton, William Anderst, and MaCalus Hogan declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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