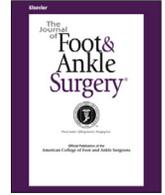




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Review Articles

Multisegment Foot Models and Clinical Application After Foot and Ankle Trauma: A Review

Sander van Hoeve, PhD, MSc¹, Martijn Poeze, PhD, MSc^{1,2}¹ Professor, Division of Trauma Surgery, Department of Surgery, Maastricht University Medical Center, Maastricht, The Netherlands² Professor, School for Nutrition and Translational Research in Metabolism, NUTRIM, Maastricht, The Netherlands

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ABSTRACT

Since the end of the 1990s, several multisegment foot models (MSFMs) have been developed. Several models were used to describe foot and ankle kinematics in patients with foot and ankle pathologies; however, the diagnostic value for clinical practice of these models is not known. This review searched in the literature for studies describing kinematics in patients after foot and ankle trauma using an MSFM. The diagnostic value of the MSFMs in patients after foot and ankle trauma was also investigated. A search was performed on the databases PubMed/MEDLINE, Embase, and Cochrane Library. To investigate the diagnostic value of MSFMs in patients after foot and ankle trauma, studies were classified and analyzed following the diagnostic research questions formulated by Knottnerus and Buntinx. This review was based on 7 articles. All studies were published between 2010 and 2015. Five studies were retrospective studies, and 2 used an intervention. Three studies described foot and ankle kinematics in patients after fractures. Four studies described foot and ankle kinematics in patients after ankle sprain. In all included studies, altered foot and ankle kinematics were found compared with healthy subjects. No results on patient outcome using MSFMs and costs were found. Seven studies were found reporting foot and ankle kinematics in patients after foot and ankle trauma using an MSFM. Results show altered kinematics compared with healthy subjects, which cannot be seen by other diagnostic tests and add valuable data to the present literature; therefore, MSFMs seem to be promising diagnostic tools for evaluating foot and ankle kinematics. More research is needed to find the additional value for MSFMs regarding patient outcome and costs.

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The kinematics of the foot and ankle are an intriguing topic in the literature. Today, 3-dimensional stereophotogrammetric analysis is the state-of-the-art method for analyzing foot and ankle kinematics in humans (1). Since the end of the 1990s until now, several multisegment foot models (MSFMs) have been developed and tested, varying in the number and placement of markers and in number of segments. Through the present, >20 MSFMs have been found in the literature (2–33). Recently, a model dividing the foot in 26 segments was presented (34). With this model, reproducibility and repeatability studies were performed and gait patterns in healthy subject were analyzed (35–56).

Several models were used to describe foot and ankle kinematics in patients with foot and ankle pathologies and other gait disorders (57–104). The most described pathologies were rheumatoid arthritis,

posterior tibial tendon dysfunction, and hallux rigidus. Using these MSFMs in clinical studies, with new insights in gait, implies that these models can also be used for patients after foot and ankle trauma.

The latest reviews on MSFMs found limited studies focusing on patients after foot and ankle trauma (1,43,105,106). These studies, performed in patients after foot and ankle trauma, found interesting gait patterns correlated with radiographic parameters and patient-reported outcome measures (PROMs). Hypothetically, these models can give us more insight in postoperative gait patterns (93); however, the diagnostic value of these models for patients with foot and ankle trauma is not known. The diagnostic research questions formulated by Knottnerus and Buntinx (107) can therefore be used.

Since these reviews, more reliability studies, new models, and clinical studies have been presented; therefore, a new review of this topic is warranted. In this review, a literature search for MSFMs and clinical application in patients after foot and ankle trauma was performed. Furthermore, the diagnostic value of the MSFMs in patients after foot and ankle trauma was investigated using the diagnostic research questions formulated by Knottnerus and Buntinx (107).

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Address correspondence to: Sander van Hoeve, MSc, Division of Trauma Surgery, Division of Surgery, Maastricht University Medical Center, P. Debyelaan 25, PO Box 5800, 6202 AZ, Maastricht, The Netherlands.

E-mail address: s.vanhoeve@hotmail.com (S. van Hoeve).

Materials and Methods

Search

A systematic search term was constructed with the mesh terms: ((((((kinematics) OR biomechanics) OR gait analysis) OR multi segment foot) OR multi segment foot model)) AND (((sprain) AND (foot and ankle))) OR ((fracture) AND (foot and ankle))). The databases PubMed/MEDLINE, Embase, and Cochrane Library were searched. All abstracts from the search were screened. All studies analyzing foot and ankle kinematics with an MSFM in patients after foot and ankle trauma through August 2017, in English regardless of the level of evidence, were included. Studies in other languages were excluded. Studies that did not use MSFMs, did not analyze foot and ankle kinematics, or did not analyze kinematics after trauma of the foot and ankle were excluded. The lists of references of the retrieved publications from the initial search were checked manually for additional studies not found by the electronic search. Data were extracted from these studies. Although we expected to find limited studies with variable quality and heterogeneity between studies, no meta-analysis was performed. A narrative approach was chosen; therefore, no test for data homogeneity was used.

Data Extraction

From all included studies, author, journal, year of publication, MSFM, number of MSFM segments, foot and ankle trauma injury, follow-up, study design, phase of analysis (the swing phase and/or stance phase), patients, level of evidence, and results were noted. To investigate the diagnostic value of MSFMs in patients after foot and ankle trauma, studies were classified and analyzed following the diagnostic research questions formulated by Knottnerus and Buntinx (107):

1. Phase I question: Do patients with the target disorder have different test results from normal individuals?
2. Phase II question: Are patients with certain test results more likely to have the target disorder than patients with other test results?
3. Phase III question: Among patients in whom it is clinically sensible to suspect the target disorder, does the test result distinguish those with and without the target disorder?
4. Phase IV question: Do patients who undergo the diagnostic test fare better (in their ultimate health outcomes) than similar patients who do not?
5. Phase V question: Does use of the diagnostic test lead to better health outcomes at an acceptable cost?

Results

Included Studies

The initial search revealed 184 articles, of which 5 met the inclusion criteria and were implemented in this review. Two other articles were found by checking the references. This review was therefore based on 7 articles evaluating foot and ankle kinematics with MSFMs in patients after foot and ankle trauma (69–71,75,93,94,103).

Tables 1 and 2 provide results of the 7 included studies. These studies comprised 356 subjects (372 feet), with 148 (42%) trauma patients (148 [40%] feet) and 208 (58%) subjects as controls (224 [60%] feet). Within this control group, 110 (53%) healthy subjects (126 [56%] feet) were included: 52 (25%) copers (patients with a 1-time ankle sprain without any complaints), 52 (23%) feet; 8 (4%) patients with a subtalar arthrodesis, 8 (4%) feet; and 38 (18%) contralateral noninjured legs, 38 (17%) feet (69–71,75,93,94,103). All studies were published between 2010 and 2015. Five studies were retrospective studies analyzing foot and ankle kinematics in patients several months after trauma (level 3) (70,71,75,93,94). Two studies used an intervention with tape in patients with chronic ankle instability (CAI) after trauma to analyze the effect of the intervention (level 2) (69,103). The studies were divided in 2 categories: those with patients after foot and ankle fractures and those with patients without fracture after trauma.

Foot and Ankle Fractures

Three studies described foot and ankle kinematics in patients after foot/ankle fracture, of which 2 focused on calcaneal fractures and 1 on

ankle fractures (75,93,94). These 3 studies used 4-segment foot models (the Oxford foot model and Rattanaprasert model) including the shank, rearfoot/hindfoot, forefoot, and hallux segments. Kinematics were analyzed during stance for patients after calcaneal fractures and during the stance and swing phases for patients after ankle fractures. Follow-up varied from at least 6 months to at least 2 years. The 3 studies comprised 141 patients (157 feet), 51 (36%) fractures (51 [33%] feet), 44 (31%) healthy subjects (60 [38%] feet), 38 (27%) contralateral noninjured legs (38 [24%] feet), and 8 (6%) patients after subtalar arthrodesis (8 [5%] feet) (75,93,94). The most important findings were lower speed in patients after calcaneal fractures (75,93) and lower flexion/extension and altered inversion/eversion in patients after calcaneal fractures (75,93). Furthermore, correlation with PROMs and radiographic findings were found (93). In patients after ankle fractures, lower flexion/extension in the ankle and forefoot was seen compared with healthy subjects and the contralateral leg. In addition, lower range of motion (ROM) in the other segments were found (94).

Foot and Ankle Strain After Trauma

Four studies were found to describe foot and ankle kinematics in patients after trauma without fracture (69–71,103). They all focused on patients with CAI after ankle sprain/trauma. In 2 studies, the 6-segment Ghent Foot model was used, which divides the foot into shank, rearfoot, midfoot, medial forefoot, lateral forefoot, and hallux (70,71). In addition, the 3-segment Dichary foot model was used to divide the foot into shank, rearfoot, and forefoot; the 5-segment Leardini foot model was used to divide the foot into shank, rearfoot, calcaneus, midfoot, and metatarsus (69,103). Kinematics were analyzed during both the stance and swing phases. In these 4 studies, 215 patients (215 feet) were included, 97 (45%) subjects with CAI (97 [45%] feet), 52 (24%) copers (52 [24%] feet), and 66 [31%] healthy control subjects (66 [31%] feet) (69–71,103). Two studies focused on foot and ankle kinematics after ankle sprain (70,71); the results found, in patients with CAI and copers, an altered foot position during walking and running compared with healthy subjects during the midstance and late stance/push-off phases. The studies also found altered foot position during vertical drop and sidestep in patients with CAI and copers compared with healthy subjects during the impact phase. In addition, ROM was different between the groups during vertical drop and sidestep. Two studies focused on the effect of tape during walking in patients with CAI after trauma (69,103). The studies found a more neutral foot position after taping.

Diagnostic Value of MSFMs

The 7 studies (varying from level 2 to 3) with limited patients were used to answer the diagnostic research questions formulated by Knottnerus and Buntinx (107). All studies demonstrated altered foot and ankle kinematics in patients with foot and ankle trauma compared with healthy subjects (69–71,75,93,94,103); therefore, patients with a target disorder (foot and ankle trauma) have a different test from that used with normal individuals (healthy controls). No sensitivity or specificity test was performed with MSFMs in the 7 studies (69–71,75,93,94,103). Van Hove et al (93) found correlations between ROM in patients after calcaneal trauma surgery and patients' reported satisfaction in PROM and radiographic findings. Patients with lower ROM in the subtalar joint were found to have less congruency on postoperative computed tomographic (CT) scans and lower satisfaction, as reported in PROMs. These results can answer questions 2 and 3 as formulated by Knottnerus and Buntinx (107), and indicate that patients with a certain test result (altered ROM) are more likely to have the target disorder (altered gait pattern after foot and ankle trauma) than patients with other test results (normal ROM in healthy subjects). The ROM in patients with severe fractures is more altered than that in patients with less severe

Table 1
Included studies

Author	Year	Journal	Model	Segments	Trauma	Follow-up	Level of Evidence
Fractures							
Wang et al (94)	2010	<i>Gait & Posture</i>	Oxford foot	4 (shank, hindfoot, forefoot, hallux)	Ankle fractures	>1 y	3
Hetsroni et al (75)	2011	<i>Journal of Trauma</i>	Rattanaprasert	4 (shank, rearfoot, forefoot, hallux)	Intra-articular calcaneal fractures	>2 y	3
Van Hove et al (93)	2015	<i>Journal of Bone and Joint Surgery</i>	Oxford foot	4 (shank, hindfoot, forefoot, hallux)	Intra-articular displaced calcaneal fractures	>6 mo	3
CAI							
De Ridder et al (70)	2013	<i>Medicine and Science in Sports and Exercise</i>	Ghent foot	6 (shank, rearfoot, midfoot, medial and lateral forefoot, hallux)	CAI after ankle sprain	>3 mo after sprain	3
Chinn et al (69)	2014	<i>Journal of Athletic Training</i>	Dichary	3 (shank, rearfoot, forefoot)	CAI after ankle sprain	—	2
De Ridder et al (71)	2015	<i>Clinical Biomechanics</i>	Ghent foot	6 (shank, rearfoot, midfoot, medial and lateral forefoot, hallux)	CAI after ankle sprain	>3 mo after sprain	3
Deschamps et al (103)	2016	<i>Journal of Science and Medicine in Sport</i>	Leardini foot (Rizzoli)	5 (shank, rearfoot, calcaneus, midfoot, metatarsus)	CAI	—	2

Abbreviation: CAI, chronic ankle instability.

fractures. The test can distinguish patients with severe gait patterns (as clinically suspected by walking pattern, PROM, or radiographic findings) from patients with better/normal walking patterns. The 7 studies could not answer the other 2 questions formulated by Knottnerus and Buntinx (107). None of the studies presented data regarding better outcome or lower costs using an MSFM for patients after foot and ankle trauma (69–71,75,93,94,103).

Discussion

In this scoping review, studies focusing on foot and ankle kinematics in patients after foot and ankle trauma using MSFMs were searched. This scoping review presented 7 studies analyzing foot and ankle kinematics. Three articles focused on foot and ankle kinematics in patients after foot and ankle fractures (75,93,94), 2 focused on calcaneal fractures, and 1 on ankle fractures. Gait studies focusing on these fractures are limited, and therefore it is difficult to compare the MSFM kinematic results with other gait models and other gait studies. In the study of Wang et al (94) in 2010, foot and ankle kinematics in patients after ankle fracture were presented. Earlier studies found lower walking speed and reduced dorsiflexion and gait asymmetry with plantar pressure measurements (108,109). Wang et al (94) also found altered motion in the forefoot and hallux and altered motion, which could indicate a compensation mechanism; therefore, this study confirmed previously known data and added data on forefoot kinematics in patients after ankle trauma.

Regarding calcaneal fractures, using the foot as a rigid segment, Bozkurt et al (110) and Kitaoka et al (111) found diminished active ROM for the fractured foot at the ankle in patients with conservative treatment for calcaneal fractures. In a study by Kingwell et al (112), lower ROM in the subtalar joint was found during physical examination, and strong correlations were found between ROM in the subtalar joint and patient satisfaction reported in PROMs. Using an MSFM, Hetsroni et al (75) confirmed these findings, with lower subtalar ROM in patients after calcaneal fractures, and van Hove et al (93) found altered kinematics. In addition, inversion/eversion ROM was significantly correlated with PROM and radiographic findings (postoperative step-off in the posterior facet of the subtalar joint on CT scans). They also found higher abduction/adduction ROM between the hindfoot and tibia during push-off, indicating a compensation mechanism.

Four articles described foot and ankle kinematics in patients with CAI after ankle sprain (69–71,103). De Ridder et al (70) found a more everted position of the foot during stance in the CAI and copers groups compared with healthy subjects during normal walking; however, previous studies on this topic showed a more inverted position of the foot (113,114). Overall, this study found significant differences in mid- and forefoot kinematics that were unseen with a rigid foot model. In addition, in their second study, de Ridder et al (71) found altered kinematics in patients after CAI and copers using an MSFM during side jump and vertical drop. For the copers, a higher ROM (dorsiflexion) in the rearfoot compared with the CAI group was found during side jump; less ROM in the medial and lateral forefoot during both tasks was also found. These results can be seen as compensatory mechanisms and could protect ankles from giving way and from ankle sprains. Chinn et al (69) in 2014 and Deschamps et al (103) in 2016 used MSFMs to evaluate the effect of tape on foot and ankle kinematics in patients after ankle sprain. Both studies found altered position of the foot with tape compared with that without tape.

MSFMs seem to be a promising diagnostic tool to analyze foot and ankle kinematics in patients after foot and ankle trauma. The articles described previously reveal additional data on foot kinematics that cannot be seen with a rigid foot model or other gait analysis instruments; in particular, compensation mechanisms of the foot and ankle in patients after trauma were not seen previously. All studies demonstrated altered foot and ankle kinematics in patients with foot and ankle trauma compared with healthy subjects (69–71,75,93,94,103), thereby answering question 1 as formulated by Knottnerus and Buntinx (107). As seen in patients after ankle fractures and patients after calcaneal fractures, ROM in the ankle and subtalar joint is altered compared with that in healthy subjects (75,93,94). Patients with a target disorder (foot and ankle trauma) therefore have a different test than that used with normal individuals (healthy controls). MSFMs can find differences between healthy subjects and patients after foot and ankle trauma, but they cannot distinguish between patients with different fractures. In both the ankle fractures and calcaneal fractures groups, flexion/extension was lower in the ankle joint (93,94); therefore, MSFMs cannot be seen as diagnostic tools for trauma fractures but only as objective tools to measure quality and quantity of motion in the foot and ankle after trauma. Regarding questions 2 and 3 by Knottnerus and Buntinx (107), the answers can be found in van Hove et al (93), who found

Table 2
Study results

Author	Study Design	Phase	Result Highlights
Fractures			
Wang et al (94)	Retrospective: 18 ankle fractures versus 18 noninjured legs and controls	Stance and swing	<ul style="list-style-type: none"> - Less plantarflexed and lower flexion ROM hindfoot/tibia after ankle fracture compared with the noninjured leg (swing) - Decreased abduction/adduction forefoot/hindfoot after ankle fracture compared with the noninjured leg and controls (swing) - A less dorsiflexed hallux and less flexion/extension motion in the hallux after ankle fractures compared with the noninjured leg
Hetsroni et al (75)	Retrospective: 20 calcaneal fractures versus 20 noninjured legs and 9 controls (18 feet)	Stance	<ul style="list-style-type: none"> - Significant lower speed in calcaneal fractures compared with controls - Lower maximum subtalar eversion in calcaneus fractures compared with controls
van Hove et al (93)	Retrospective: 13 calcaneal fractures versus 8 subtalar arthrodesis and 17 controls (24 feet)	Stance	<ul style="list-style-type: none"> - Significant lower speed in calcaneal fractures - Lower flexion/extension between hindfoot/tibia in calcaneal fractures compared with controls - Lower inversion/eversion between forefoot/tibia in calcaneal fractures compared with controls - Significant correlation between inversion/eversion and PROMs and postoperative step-off in the posterior facet of the subtalar joint
CAI			
De Ridder et al (70)	Retrospective: 29 CAI patients versus 24 copers and 24 controls	Stance	<ul style="list-style-type: none"> - A more everted position of the rearfoot related to shank in CAI and copers groups compared with controls - A more inverted position of the medial forefoot related to the midfoot in CAI and copers groups compared with controls
Chinn et al (69)	Intervention study: 15 CAI with and without taping	Stance and swing	<ul style="list-style-type: none"> - Less plantar flexion and less inversion in the ankle in the taped group compared with the untaped group during walking - Less dorsiflexion and less inversion in the ankle during jogging in the taped group
De Ridder et al (71)	Retrospective: 38 CAI, 28 copers, 30 controls	Stance/impact during vertical drop and side jump	<ul style="list-style-type: none"> - A more inverted position of the midfoot related to the rearfoot in the CAI group compared with controls during side jump - More midfoot inversion/eversion motion in the CAI group compared with copers during vertical drop - A more adducted hallux position for patients with CAI and copers compared with controls during vertical drop - Less flexion/extension motion in the copers group compared with the CAI group during side jump - Less flexion/extension in the medial and lateral forefoot during side jump/vertical drop for copers compared with controls
Deschamps et al (103)	Intervention study: 15 CAI with and without tape, 12 controls	Stance and swing	<ul style="list-style-type: none"> - Controls ran significantly faster and had shorter stance time and longer swing time compared with the CAI group - Decreased dorsiflexion and increased inversion between the shank and rearfoot and a more internally rotated foot in the CAI group compared with controls - A more adducted calcaneus in the CAI group - A more dorsiflexed angle between the calcaneus and shank in patients with high-dye tape compared with low-dye tape - A more inverted angle between the midfoot and metatarsus in patients with low-dye tape compared with CAI subjects

Abbreviations: CAI, chronic ankle instability; ROM, range of motion.

correlations between ROM in patients after calcaneal trauma surgery and patient satisfaction reported in PROM and radiographic findings. Patients with lower ROM in the subtalar joint were found to have less congruency on postoperative CT scans and lower satisfaction as reported in PROMs, which indicates that patients with a certain test result (altered ROM) are more likely to have the target disorder (altered gait pattern after foot and ankle trauma) than patients with other test results (normal ROM in healthy subjects). In addition, patients with lower congruency of the subtalar joint show lower ROM compared with patients with better congruency of the subtalar joint; therefore, among patients in whom it is clinically sensible (altered walking pattern and less congruency on CT scans) to suspect the target disorder (altered gait pattern), the level of test result can distinguish those with and without the target disorder. The ROM in patients with severe fractures is more altered than in patients with less severe fractures. The test can distinguish patients with severe gait patterns (as clinically suspected by walking pattern, PROM, or radiographic findings) from patients with better/normal walking patterns. Healthy subjects with no foot and ankle trauma can also have altered gait patterns from other causes (e.g., ischemic cerebral stroke, arthritis, stiffness); however, the additional value of MSFMs regarding outcome and costs is not known. Following

the diagnostic questions by Knottnerus and Buntinx (107), MSFMs are promising in finding differences between healthy subjects and patients after foot and ankle trauma. Although the use of these findings regarding patient outcome and costs reducing is lacking, to date, no studies were found describing the use of MSFMs for a better outcome for patients after foot and ankle trauma or lower health care costs.

In the future, more segmented models with good reliability can add valuable data on foot and ankle kinematics in patients with foot and ankle trauma. With better understanding of kinematics of healthy subjects and altered kinematics in patients after foot and ankle trauma before and after surgery, data analysis should be performed. Analyzing important factors in kinematics and patient satisfaction therapies can be undertaken to improve patient outcome by operative repair and rehabilitation.

An important item in MSFMs is cost. Movement laboratories are expensive. No data on costs are presented in the 7 studies. As seen in patients after calcaneal fractures, social costs are very high because of pain and the inability to work (93). With MSFMs, a better understanding in foot and ankle kinematics may lead to better understanding of fracture repair and recovery, which can therefore reduce some amount of social costs. Future studies analyzing costs can add valuable

information. MSFMs should be used for research purposes in dedicated centers. Significant new findings can be used afterward to improve health care for all patients around the world. Patients suffering after trauma in centers without gait analysis capabilities can be sent for a second opinion for further research to analyze gait and make adjustments in footwear, prescribe specific exercises, or schedule revision surgery.

This scoping review has some limitations. First, the amount of studies is limited. Only 7 studies analyzing patients after foot and ankle trauma using MSFMs were found. MSFMs have been used for more than a decade. More than 20 models are described in the literature; these models show good reproducibility, but the materials are expensive and measuring is time consuming. Use is therefore still limited. In addition, these studies used limited patients. In some studies, healthy subjects were used; in other studies, contralateral legs or other patients (with subtalar arthrodesis) were used. Some studies analyzed both the swing and stance phases, whereas others analyzed only the stance phase. In addition, different MSFM models with a different number of segments were used. Therefore, there is a lot of heterogeneity between these studies, and a meta-analysis was not performed.

In conclusion, to date, 7 studies with MSFMs reporting foot and ankle kinematics in patients after foot and ankle trauma are reported. Results show altered kinematics that cannot be seen by other diagnostic tests and add valuable data to the present literature; therefore, MSFMs seem to be a promising diagnostic tool for evaluation of foot and ankle kinematics. More research is needed to find additional value for MSFMs regarding patient outcome and costs.

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