A noninvasive method of assessing the motion of the subtalar joint was developed for use in clinical and research settings. Anatomical reference frames for the calcaneus and talus were produced using a marker placement model utilizing 14 markers. An asymptomatic individual was tested during barefoot walking with a CODA MPX30 system. Intertrial variability and motion patterns, in all three planes, of the calcaneus with respect to the talus were analyzed as part of a validation study. The observed patterns in all three planes were found to have good face validity with published literature as well as good consistency during stance. The findings of this study support the further use of this model in both clinical and research settings, allowing investigation of the motion patterns of a larger cohort than has hitherto been possible. (J Am Podiatr Med Assoc 104(1): 103-109, 2014)

The contribution of subtalar joint (STJ) kinematics to foot function has been the focus of much research.\textsuperscript{1,2} Roentgen stereophotogrammetry, two-dimensional (2-D) video-analysis, finite and analytic analysis, magnetic resonance imaging studies, and static and dynamic cadaver models have all contributed to the current body of knowledge of STJ kinematics. Although these studies have provided important information, they all have limitations with respect to the in vivo measurement of dynamic weightbearing STJ movement. Data have also been produced using invasive, in vivo techniques, although the impact of the methodology on the data remains debatable, and the use of such techniques is unlikely to be applicable in the clinical context. The use of in vivo skin-mounted markers based on 3-D modeling techniques could allow the collection of data from significant numbers of individuals and form the basis of a clinically usable technique. Although a number of 3-D multisegment foot models have been published,\textsuperscript{3} critical appraisal reveals that the STJ has rarely been investigated in isolation of other joints, the motion of the STJ often being integrated with that of the rearfoot complex.

Recently, Birch and Deschamps\textsuperscript{4} proposed a marker placement protocol for modeling STJ kinematics, including markers at the malleoli, calcaneus, and talus head. Results of static repeatability trials were reported and showed the model to produce repeatable data. The quantification of skin marker movement at the malleoli and talus head and the associated impact on the marker placement model’s validity has also been investigated.\textsuperscript{5} This work showed the effect of skin movement on marker placement and calculated intersegmental angles to be less than might have been expected.

We report preliminary observations from STJ kinematics quantified with this novel, noninvasive marker placement protocol recently published by Birch and Deschamps.\textsuperscript{4}

**Methods**

The marker placement model described by Birch and Deschamps\textsuperscript{4} was used to locate 14 markers, each of which measured approximately 20 × 10 mm, on the right foot and leg of a right-side dominant, symptom-free male (age, 48 years; weight, 82 kg), together with seven marker driver boxes (Fig. 1). The anatomical locations of the markers are listed in Table 1. The subject’s foot type was assessed by a qualified podiatrist and described as being mobile, medium to high arched. Two segments, considered
to be rigid bodies, were defined: the talus and calcaneus. The calcaneus was defined using four markers (Fig. 2A). The x-axis was defined by a vector drawn between the posterior medial calcaneus marker and the posterior lateral calcaneus marker; the y-axis was defined as being at right angles to the x-axis in the direction of a virtual mid-anterior marker calculated from the anterior medial calcaneus marker and anterior lateral calcaneus marker. The talus was defined using the medial and lateral talus markers and a mid-ankle virtual marker located midway between the medial and lateral malleolus markers (Fig. 2B). The x-axis of the talus was defined as a vector drawn between the medial and lateral talus markers, and the y-axis was defined as a vector at a right angle to the x-axis in the direction of the mid-malleolus virtual marker. For

**Figure 1.** Marker placement at the foot and lower limb including seven marker driver boxes.

**Figure 2.** Definition of the rigid segments: (A) calcaneus, (B) talus. Four bony landmarks were used to construct the calcaneal and talar anatomical reference frame.

<table>
<thead>
<tr>
<th>Anatomical Locations of the Markers Used in This Study</th>
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<tbody>
<tr>
<td><strong>Leg</strong></td>
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<tr>
<td>Head of the fibula</td>
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<tr>
<td>Medial condyle of the tibia</td>
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<tr>
<td>Tuberosity of the tibia</td>
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<td>Distal anterior tibia</td>
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<td>Medial malleolus</td>
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<tr>
<td>Lateral malleolus</td>
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<tr>
<td><strong>Talus</strong></td>
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<tr>
<td>Medial head of talus</td>
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<tr>
<td>Lateral head of talus</td>
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<tr>
<td><strong>Calcaneus</strong></td>
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<tr>
<td>Posterior medial calcaneus</td>
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<td>Posterior lateral calcaneus</td>
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<tr>
<td>Anterior medial calcaneus</td>
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<tr>
<td>Anterior lateral calcaneus</td>
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<tr>
<td><strong>Forefoot</strong></td>
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<tr>
<td>First metatarsophalangeal joint</td>
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<tr>
<td>Fifth metatarsophalangeal joint</td>
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104 January/February 2014 • Vol 104 • No 1 • Journal of the American Podiatric Medical Association
both bones, the mutually orthogonal z-axis was determined by the position of the x- and y-axes.

Two CODA MPX30 sensor units (Charnwood Dynamics Ltd, Rothley, United Kingdom), positioned parallel at either end of a 7-m walkway, were used to track marker motion. The left-hand edge of each sensor unit was aligned with the midline of the walkway, resulting in the sensor units being offset in opposite directions. This strategy was adopted to prevent reflected light from the medial markers producing erroneous data. One hundred data sets were collected on the same day with the participant walking at a self-selected speed. A self-selected walking speed was used to ensure that the participant assumed as normal a gait pattern as possible throughout data collection. Each data set recorded approximately four right steps with a measurement frequency of 200 Hz. A low-pass filter with a cut-off frequency of 10 Hz was applied to the angular data. A mid-gait protocol was used for the selection of a single step. A combination of marker linear acceleration and vector angular velocity were used to identify heel strike and toe-off, allowing the identification of a total of 100 contact phases.

The talus markers and virtual markers were then used to perform a coordinate transformation, allowing the measurement of the movement of the calcaneus in relation to the talus, the talus thus providing the definitions of the frontal, transverse, and sagittal planes.

All data were temporally normalized using a cubic spline interpolation to produce 150 data points per total stance phase. This number of data points was

![Figure 3. Summary of the movement of the subtalar joint during the contact phase of walking as shown by this study.](image-url)
easily divisible into percentages for comparison with previous investigations and a compromise between the largest and smallest number of data points captured in a single gait cycle.

Results

For each plane, mean and ±1 SD graphs were produced (Fig. 3), showing a good consistency of the data during stance. An initial short period of inversion, from heel strike until 5% of stance, was followed by a long period of eversion, from 5% until 85% of stance. This was followed by a short period of inversion until toe-off. In the sagittal plane, a short period of plantarflexion was followed by a long period of dorsiflexion from 5% to 60% of the contact phase. The calcaneus was then shown to plantarflex from 60% until 75% before dorsiflexing until 90% of stance. During the final 10% of stance, the calcaneus showed slight plantarflexion followed by rapid dorsiflexion. In the transverse plane, heel strike was followed by rapid adduction for the first 5% of stance. This was followed by slight abduction then adduction and a longer period of slight abduction lasting until approximately 35% of stance. The calcaneus was then shown to adduct until 85% of stance before finally abducting until toe-off.

Discussion

In this study, motion data was described as absolute movement occurring at the STJ in each of the three planes, rather than the movement relative to a neutral position. This technique was employed in view of the substantial variations in methodology used in previous studies to define a neutral position. This variation impedes direct comparison with earlier studies. To overcome this difficulty, Figures 4–6 show the graphical representations of data produced by the various authors, grouped around the timing of the 50% of stance phase point.

In general, despite the fact that the initial frontal plane movement is shown to be in the opposite direction to that indicated by other studies, the frontal plane data is not an unreasonable pattern of STJ movement during stance. The range of movement of 4.22 degrees is also within the spread of ranges shown by other authors. Similarly, the

![Graphical comparison of frontal plane movement (eversion/inversion) between calcaneus relative to the talus observed in the current study and by other investigators.](image)

Figure 4. Graphical comparison of frontal plane movement (eversion/inversion) between calcaneus relative to the talus observed in the current study and by other investigators.
sagittal plane movement pattern shown in this study is not unlike that shown by previous authors. In the case of the sagittal plane data, the initial dip (plantarflexion) is matched by a similar dip by Arndt et al’s subject three and the trace quantified by Michelson et al. Additionally, the movement pattern observed at the end of stance showed good similarity with all three of Arndt’s subjects.1 The initial adduction is also shown in the data of Arndt et al1 and Hamel et al.8 The final period of abduction is again shown by Hamel8 and Michelson’s data.7 In general terms, the data from our study show a similarity to that of Hamel and Michelson, but less of a similarity to that of Arndt.

The data collected by Arndt et al,1 Hamel et al,8 and Michelson et al7 were collected using very different methodologies. Hamel et al8 and Michelson et al7 used cadaver legs and feet, a machine for simulating walking, and bone-mounted markers. The advantage was that skin movement was not a factor, the disadvantage being a questionable validity of the gait produced by the walking simulator. Their results were also presented in terms of an average pattern of movement for the eight specimens; individual differences were not presented although the standard deviations from the mean traces were presented. Interestingly these standard deviations showed the widest variations to occur immediately after heel strike and immediately prior to toe-off, as was found in this study. Arndt et al1 used an in vivo methodology with bone-mounted markers. The advantages were that this was genuine walking and that skin movement was not an issue. The disadvantage was that the number of study participants was limited and that, despite their best efforts to minimize the possibility, the mounting of marker clusters directly into the bone of the participants could have affected gait and therefore subtalar joint movement during data collection.

In view of variability in STJ structure, variability between study participant data should be expected.9,15 Consideration should also be given to the comparison of data produced by kinematic studies and the general theories of STJ motion. Root et al11 and Scott and Winter16 all suggested that heel strike was immediately followed by pronation (eversion, abduction, and dorsiflexion) of the STJ. The findings of the current study and other recent studies.1,7-8

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**Figure 5.** Graphical comparison of sagittal plane movement (plantarflexion/dorsiflexion) between calcaneus relative to the talus observed in the current study and by other investigators.
would suggest that in some cases there is an initial period of slight supination (inversion, adduction, and plantarflexion) before the STJ pronates. The results of the later studies also question the concept of the STJ as being a simple tightly bound hinge joint. Several authors considered this to be an oversimplification, suggesting that the relationship between the talus and the calcaneus is a more flexible one, allowing a wider range of options in terms of movement combinations than would be the case in a tightly bound hinge joint.

The limitations of this study were that the movement pattern shown was representative only of the single study participant and that skin movement could have been a significant confounding factor, although the findings of Birch and Deschamps suggest that the influence of skin movement on the data may be somewhat less than might have been expected. It is recognized that the viability of any motion analysis methodology, particularly one to be used to quantify the motion of the STJ, relies on its ability to be used on multiple individuals. However, the purpose of our study was to test the viability of the methodology in terms of its ability to produce repeatable and feasible results. As such, the use of a single study participant was an appropriate approach at this stage of development, limiting the number of uncontrolled variables. In this study, we have shown the methodology to produce repeatable and feasible results; a further study is required to assess the use of this methodology with multiple individuals. This further study will take into account the anatomical and functional variations exhibited by multiple participants, such as foot size and type, the amount of adipose tissue, and differential skin movement.

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**Conflict of Interest:** None reported.

**References**


