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Optimal Ankle Axis Position for Articulated Boots

DUSTIN BRUENING and JAMES G. RICHARDS

ABSTRACT
An articulated boot design is commonly used in skiing and skating sports because it allows sagittal plane ankle mobility while still providing critical frontal plane stability. Although articulated boots have been in use for several decades, current manufacturers of these boots differ in their articulation placement. In this study we determined an optimal position of the ankle articulation axis. We also calculated the amount of anterior skin movement that a boot tongue must account for during a full range of ankle motion. Three-dimensional kinematic data were collected and analyzed from 40 participants moving their right foot through a full range of sagittal plane motion. The calculated horizontal position of the articulation axis was found to be highly predictable from foot length ($r = 0.87$, standard error of estimate = $3.44 \text{ mm}$), while its vertical component displayed less predictability ($r = 0.49$, standard error of estimate = $7.46 \text{ mm}$). The expansion required by the boot tongue had a moderate association with foot length and low variability ($r = 0.58$, standard error of estimate = $0.07 \text{ mm}$). An accurate axis placement will minimize relative motion between the boot cuff and the ankle, reducing friction and motion resistance. An expandable tongue will accommodate full plantar flexion and reduce pressure on the anterior ankle during dorsiflexion, eliminating common pressure-related injuries.

Key words: ankle axis, articulation, boots, skiing, skating

INTRODUCTION
Skiing and skating sports are enjoyed by millions of people throughout the world. These sports have similar footwear characterized by an external blade or ski attached to a stiff boot. Frontal plane stability is a particularly important concern in skiing and skating boots because of the added lever arm of the blade or ski. This increases the length and height of the rigid foot segment, magnifying the external moments acting on it. When external inversion and eversion moments are high, balance is compromised and ankle ligaments are susceptible to injury. Although frontal plane support is critical, it should not interfere with sagittal plane mobility. Dorsiflexion and plantar flexion are essential in performance as well as in injury prevention. Research on jump landings provides some insight.
into the relationship between sagittal plane joint mobility and injuries caused by ground reaction forces. These studies suggest that increased joint flexion upon landing can reduce high impact forces (Lees, 1980; Devita and Skelly, 1992; Zhang et al., 2000). A phased segmental deceleration of body segments allows the joint musculature to spread impacts over a longer time, reducing peak forces and high loading rates. Specifically, increased ankle plantar flexion upon landing allows the triceps surae complex to slow the descent of the heel, resulting in a lower peak ground reaction force (Gross and Nelson, 1988; Self and Paine, 2001).

Alpine ski boots evolved from a traditional above-ankle leather boot to a two-part, articulated plastic boot in 1959. The articulation allowed the ankle some freedom of motion for dorsiflexion while the stiff plastic limited foot inversion and eversion. In-line skates and several brands of hockey skates followed suit with their own articulated boots. These designs have allowed athletes to perform increasingly more difficult maneuvers with comparatively fewer injuries. Other currently non-articulated boots and ankle braces may also benefit from an articulation.

**Axis location**

While an articulated boot design is not new, current models vary in the location of the articulation. In an in-house comparison of four ski boot manufacturers, the articulation in a 275 mm length boot showed sagittal plane variations of approximately 30 mm both horizontally and vertically. In-line and hockey skates showed even greater variability of up to 40 mm. If the articulation is not located near the centre of constrained ankle joint rotation, the boot cuff will slide on the shank as the ankle moves between plantar flexion and dorsiflexion. This extra cuff motion will increase with the range of motion allowed by the boot’s articulation. Cuff sliding may cause discomfort, bruising and inflammation of the tissue surrounding the ankle. An inappropriate articulation placement can also limit the range of motion, increase motion resistance and alter joint compression loads. In this study we offer a rationale for a standard articulation placement that will minimize relative cuff motion.

**Axis orientation**

Most current articulated skiing and skating boot designs use a transverse axis that confines ankle motion to the sagittal plane. Although this is often done solely for ease of manufacturing, we agree that an articulated boot should use a transverse axis because it correctly positions the lower body for normal mechanics. The rationale behind this orientation requires a discussion of the anatomical axes of the ankle joints.

The ankle consists of two separate but dependent joints. The talocrural, or true ankle joint, is formed by the boundary of the tibia, fibula and talus. Slightly inferior, the talus and calcaneus form the subtalar joint. The talocrural joint is often considered to be responsible for plantar flexion and dorsiflexion, while the subtalar joint controls inversion and eversion. The exact anatomical axis or axes of the talocrural joint are still contested. Several researchers have suggested that
a single axis can be used to describe talocrural motion (Inman, 1976; Singh et al., 1992). This oblique axis is offset by about 20° in both the transverse and frontal planes. Others claim that there are multiple axes of rotation and that the axis in dorsiflexion differs by as much as 20–30° from the axis in plantar flexion (Barnett and Napier, 1952; Hicks, 1954; Lundberg et al., 1989a; Hintermann and Nigg, 1995).

When adding an articulation to a boot it may at first seem anatomically appealing to try to mimic the talocrural axis or axes. However, doing so would introduce joint alignment issues because of the additional constraints imposed by the rigid boot and the blade or ski. In closed chain ankle and knee flexion, the tibia should progress directly over the foot, keeping the centre of pressure in the sagittal plane. Movements that displace segments out of this alignment have the potential to increase the risk of injury by placing loads on the weaker frontal plane muscles and ligaments. These loads are magnified in skiing and skating by the increased lever arm of the ski or blade. In normal mechanics, planar motion is accomplished through a combination of talocrural and subtalar motion as well as tibial rotation. These integrated motions help position the talocrural joint so that the shank can progress in the sagittal plane. Because a single axis, rigid boot also affects and limits these complimentary motions, the goal of an articulated boot should not be to copy the multiple and interdependent anatomical axes, but simply to allow the motion to stay in planar alignment. The axis is, therefore, not an individual-specific anatomical axis but a constrained motion axis. Constraining the motion to the sagittal plane will limit the potential for abnormal motion in the other planes. A helpful analogy may be the effect that a medial wedge in a plantar orthotic has on controlling three-dimensional motion of the rear foot. The wedge constrains the rear foot so as to limit out of plane motions caused by excessive pronation.

Tongue limitations
A fully mobile articulated boot design introduces another unresolved issue. As the ankle dorsiflexes, the skin along the anterior surface of the ankle changes length as the muscles contract and shorten the distance between the foot and shank. A traditional tongue is compressed in full dorsiflexion, creating pressure on the anterior ankle tissues. Tongue pressure can cause bruising and inflammation of the anterior ankle tissue. A traditional inflexible tongue also resists and limits full plantar flexion. The limitations of a traditional tongue have not been as great an issue in skiing and some forms of skating, because the range of motion is limited to 10–20°. However, for articulated figure and hockey skates, as well as possible ankle brace and shoe designs, a greater range of motion is desirable. As the range of motion increases, the tongue of the boot must correspondingly account for the shortening and lengthening of the anterior ankle tissue.

Aims
If a fully mobile articulated boot is to function effectively, the articulation must be located as close as possible to the axis of constrained ankle rotation and the
tongue of the boot must allow for the associated increased range of motion. To
design an effective articulated boot, the axis of rotation must be identified and
the amount of anterior skin motion must be quantified. The aims of this study,
therefore, were to determine the ideal location for a single articulation that would
allow exclusively sagittal plane motion and to quantify the skin movement along
the anterior portion of the ankle during a full range of motion.

METHODS
Forty volunteers, varying in age from 8 to 30 years (mean ± SD = 18.1 ± 6.5),
participated in this study. The participants represented a range of foot sizes,
190–290 mm (mean = 240 mm), and were free from any lower extremity injuries
at the time of testing. The Institutional Review Board approved the study.

A small apparatus, similar to a gas pedal, was constructed using wood and
hinges. Participants were seated and barefoot, with the right foot strapped to the
apparatus (Figure 1). For our purposes, this seated, non-weight-bearing position
provided a more controlled and accurate testing environment than a standing,
weight-bearing test. A full weight-bearing motion would introduce greater
variability owing to the additional effort required to keep the motion planar as
well as the difficulties in controlling structural differences such as rear foot
pronation and tibial torsion. Again, the axis is not an individual-specific
anatomical axis, for which a weight-bearing position would be required, but a
general constrained motion axis. Additionally, although much of the ankle motion
in skiing and skating is weight-bearing, many critical movements, such as
preparation for landing, are not weight-bearing. In the seated and fixed con-
figuration that our apparatus provided, the ankle motion was confined to the
sagittal plane and out-of-plane variability was minimized.

Only the right foot of each participant was tested. Thirteen 6 mm retro-
reflective markers were attached with double-sided tape to the participant’s foot
and lower leg, and to the apparatus. The markers were placed on the following
anatomical landmarks: femoral epicondyles, tibial tuberosity, medial and lateral
malleoli, and the tip of the halux. Four markers were placed in a column along
the anterior surface of the ankle to measure the skin contraction and expansion
during ankle motion (Figure 1). In addition, three markers were placed on the
board to create a local three-dimensional coordinate system with an origin at the
posterior-inferior border of the heel (Figure 1).

Each participant moved his or her right foot through a full range of dorsi-
flexion and plantar flexion. Participants were instructed to keep their right knee
in the same plane as the foot during the movement. A retrospective analysis
revealed the maximal out-of-plane knee motion to be 1.5 ± 0.8°, or 10 ± 5 mm.
The marker positions were recorded at a frequency of 60 Hz by an eight-camera
Eagle digital camera system with EVa Real-Time integrated software (Motion
Analysis Corporation, Santa Rosa, CA).

The Labview graphical interface programming language (National Instru-
mements Corporation, Austin, TX) was used to analyze the data. The positions of
all markers were first rotated into the local coordinate system defined by the foot
and board. The data were then reduced to two dimensions to simplify analysis.
The ankle motion axis was found from a two-dimensional circle-fitting procedure. The tibial marker moved in an arc relative to the foot’s coordinate system. A circle was fitted to the points of this arc and the centre of the circle was designated as the ankle axis position. In the circle-fitting algorithm, the distance between each point and the surface of the circle is defined by:

\[ d_i = r - \sqrt{[(x_i - x_o)^2 + (y_i - y_o)^2]} \]

where \( r \) is the radius of the circle, \( x_o, y_o \) is the centre of the circle, and \( x_i, y_i \) is a point in the data set. This distance was minimized using a least squares approach and solved with singular value decomposition (Forbes, 1989).

Another arc created by the knee centre – the midpoint between the two femoral epicondyle markers – was used to measure each participant’s range of motion. Zero flexion was defined as the frame at which the knee centre was directly superior to the ankle centre.

The anterior skin motion was calculated as a linear change in distance between each of the four column markers. As the foot moved from full plantar flexion to full dorsiflexion, the markers moved closer to each other. The change in linear distance between adjacent markers was calculated and summed, producing a total length change at each frame of movement. This value was then divided by the flexion angle to describe the parameter in millimeters per degree of flexion. Because the centre point of each marker was 3 mm from the skin, this measurement approximated the motion required by the tongue of the boot, which also lies a few millimeters off the ankle surface.
A linear regression analysis was used to determine the relationships between the independent variable – foot length – and the dependent variables – ankle centre positions, malleoli positions, and anterior ankle skin motion.

**RESULTS**

The axis and malleoli positions displayed linear relationships with foot size. All correlations were significant at \( p < 0.05 \). Table 1 summarizes the correlation coefficients, standard errors, and regression equations for the horizontal (x) and vertical (y) components of the axis and malleoli positions. The table also includes the results for the anterior skin movement, which ranged from 0.78 to 1.17 mm per degree of flexion and displayed a significant linear relationship with foot size.

**Table 1** Summary of regression analysis showing the correlation coefficients (\( r \)), standard errors (\( s_{xy} \)), and regression equations relating all dependent variables with foot length (\( L \)). All units are millimeters except tongue motion, which is described in millimeters per degree of flexion.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>( r )</th>
<th>( s_{xy} )</th>
<th>Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axis Position</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>0.87</td>
<td>3.44</td>
<td>( x = 0.265 \times L - 4.70 )</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.49</td>
<td>7.46</td>
<td>( y = 0.182 \times L + 25.3 )</td>
</tr>
<tr>
<td><strong>Medial Malleolus Position</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>0.68</td>
<td>5.54</td>
<td>( x = 0.224 \times L + 4.58 )</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.72</td>
<td>7.53</td>
<td>( y = 0.337 \times L + 3.90 )</td>
</tr>
<tr>
<td><strong>Lateral Malleolus Position</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>0.71</td>
<td>5.32</td>
<td>( x = 0.234 \times L - 7.26 )</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.52</td>
<td>5.84</td>
<td>( y = 0.154 \times L + 34.1 )</td>
</tr>
<tr>
<td><strong>Anterior Skin Motion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length per Degree</td>
<td>0.58</td>
<td>0.07</td>
<td>( = 0.0021 \times L + 0.456 )</td>
</tr>
</tbody>
</table>

Figures 2 and 3 show medial and lateral views of the predicted axis position for the mean foot size (240 mm) from this study. An ellipse surrounding the axis centre on these scaled representations represents a 95% confidence interval.

The average ranges of motion measured in this study were 22 ± 6° dorsiflexion and 33 ± 5° plantar flexion. Lundberg et al. (1989b) summarized the results of many previous studies done on average ranges of ankle motion. They included six separate sources of goniometric and radiographic measurements showing ranges of 13 to 33° dorsiflexion and 23 to 56° plantar flexion. The average ranges of motion measured in this study were well within these reported ranges.
DISCUSSION AND IMPLICATIONS

A transverse-axis articulated boot design supports the ankle in inversion and eversion while allowing dorsiflexion and plantar flexion. Inaccurate articulation placement creates unwanted motion between the boot cuff and the shank, resulting in shearing forces that, over time, cause discomfort, bruising and inflammation as well as decreased performance. The correct placement of the articulation axis becomes more important as the range of motion increases. In some skating sports a large range of motion is required, while Alpine ski boots are perhaps the least susceptible to misalignment because of the smaller range of motion desired and allowed in these boots.
Figure 4 As the shank moves 30° about the ankle centre (O), a point on the boot cuff (B) moves about a 20 mm offset boot axis (O') and ends up 10 mm from where it began, relative to the shank (A).

A simple trigonometric calculation (Figure 4) shows the amount of cuff movement associated with a misaligned axis. As an example, we chose a hypothetical boot with an 80 mm cuff height, from the ankle centre to the top of the cuff, a range of ankle motion of 30°, and an axis that is 20 mm off-centre. If the axis is displaced 20 mm either anteriorly or posteriorly (horizontally), the top of the cuff will slide about 10 mm on the shank through the range of rotation. If the axis is displaced 20 mm either superiorly or inferiorly (vertically), the amount of cuff sliding is 2.2 mm. This simple example shows the importance of placing the axis in the proper location horizontally, keeping in mind that there may be more room for error in the vertical direction.

Besides producing excess cuff motion, a misaligned articulation will also increase motion resistance. Bottlang et al. (1999) reported energy costs associated with misaligned axes in articulated external fixation devices. Although these devices were aligned with the anatomical talocrural joint axis, the study provided some insight into the resistance associated with off-centre axes. Using inverse dynamics, the external work required to rotate the foot from 15° dorsiflexion to 25° plantar flexion was calculated for several different axis positions. Off-axis translations of 5 mm were found to require more than twice the energy of the best-fit axis position.
There may be several reasons why current boot manufacturers vary in the location of their boot articulation axes. There is currently no published research describing a constrained sagittal plane ankle axis. Any data that have been collected have been held proprietary by individual footwear manufacturing companies. Also, designers of articulated boots may be placing the axis in the most convenient location for each model’s manufacturing purposes. Manufacturing constraints certainly exert a major influence on boot design. Marketing also influences design as the axis is incorporated into the aesthetics of the boot.

For ankle axis positions, there is a very strong correlation with foot length in the horizontal (x) direction \((r = 0.87)\) while the correlation drops in the vertical (y) direction \((r = 0.49)\). The lower correlation and greater variability of the axis’ vertical component may be explained by arch differences. The wide variety of arch heights gives the human foot more structural variability in the vertical direction.

It would be appealing to identify the position of the ankle axis relative to the anatomical landmarks of the medial and lateral malleoli rather than the heel border. Although the malleoli marker positions displayed linear relationships with foot length and had moderate predictability, the relationships between the malleoli and axis positions are not statistically significant. It is an oversimplification to approximate the malleoli as single points, owing to their three-dimensional contoured form. The difficulty in identifying a point on the malleoli, combined with the inherent variability associated with the malleoli and joint axis positions, confuses the relationship between foot length and axis position when the malleoli are used as points of reference. Instead, a general observation can be made: in almost all cases, the ankle centre was located just inferior to the medial malleolus and anterior to the lateral malleolus (see Figures 2 and 3).

Designers and manufacturers of articulated footwear can use the regression equations from Table 1 to pinpoint the correct sagittal plane axis position. Clinicians or technicians working with articulated footwear may immediately spot obvious axis misalignments from a basic knowledge of the principles addressed in this paper.

The skin movement along the anterior portion of the ankle also showed a linear relationship with foot length. The low correlation coefficient is misleading because of the small change in skin movement relative to foot size. In fact, the standard deviation for this parameter was 0.08 mm per degree of flexion (mean = 0.96 mm per degree). For practical purposes, the skin movement may be estimated to be about 1 mm per degree of flexion.

With the limited range of motion that most ski boots and inline skates allow, skin movement on the anterior surface of the ankle is not problematic. However, if a more complete range of motion is desired, a traditional rigid tongue will limit the movement of the articulation. To accommodate the shortening and lengthening of the anterior ankle tissue, the tongue must either be a two-piece design or include a flexible or expandable section over the anterior ankle. There are currently no boot tongues that are constructed to accommodate a full range of ankle motion.

An articulated footwear design may also be of value in other sports in which stability is an issue. Sports, such as basketball and volleyball, which incorporate
jumping within their required skill sets have a high incidence of ankle sprains; attempts to incorporate medial and lateral support in the shoes are limited by the greater need for freedom of movement. It may be possible to use an articulated shoe for these sports, although additional work needs to be performed to determine the practical benefit of such designs.

CONCLUSION

The aim of this study was scientifically and statistically to determine two distinct parameters that should be incorporated into articulated footwear. The optimal ankle axis for such footwear is a non-anatomical motion axis that keeps the foot and shank in the sagittal plane. The location of this axis is correlated to foot size, being about 25% of the length of the foot in the horizontal direction and 21% of foot length in the vertical direction, relative to the posterior inferior border of the heel. There is more variability in the vertical direction but, fortunately, there is also more room for error in this direction. Additionally, in dorsiflexion and plantar flexion, the anterior ankle tissue shortens and lengthens by approximately 1 mm per degree of flexion. For a full range of motion, a boot tongue needs to contract and expand to account for about 55 mm of travel. We hope that the parameters quantified in this study will be used by manufacturers of articulated ski boots and in-line and ice skates. We also hope that this research will aid innovation in future articulated footwear designs.

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