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A new one-DOF fully parallel mechanism for modelling passive motion at the human tibiotalar joint

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ABSTRACT

Knowledge on how ligaments and articular surfaces guide passive motion at the human ankle joint complex is fundamental for the design of relevant surgical treatments. The paper presents a possible improvement of this knowledge by a new kinematic model of the tibiotalar articulation. Passive motion, i.e. in virtually unloaded conditions, was captured in vitro in four lower leg specimens by means of a surgical navigation system with cluster of active markers attached to the tibia and talus. The anatomical geometry of the passive structures, i.e. articular surfaces and attachment areas of the ligaments, were taken by digitisation with a pointer. An equivalent spatial mechanism for the passive motion simulation was defined by three sphere-to-sphere contact points and two rigid links. These contact points were identified at the lateral talo-fibular articulation and at the medial and lateral aspects of the articulation between tibial mortise and trochlea tali. The two rigid links were identified by the isometric fibres at the calcaneofibular and tibiocalcaneal ligaments. An optimisation algorithm was developed for the identification of the final geometrical parameters resulting from an iterative refining process, which targets best matching between model predictions and corresponding experimental measurements of the spatial motion. The specimen-specific equivalent spatial mechanisms replicated the original passive motion very well, with mean discrepancies in position smaller than 2.5 mm and in rotation smaller than 1°. The study demonstrates that the articular surfaces and the ligaments, acting together as a mechanism, control the passive kinematics of the ankle joint.

1. Introduction

Passive motion, i.e. in virtually unloaded conditions, of the human ankle joint complex still attracts attention of researchers for enhancing the comprehension of surgical treatments and in particular the design of total ankle replacement (Saltzman et al., 2000; Hintermann and Valderrabano, 2003) and ligament reconstruction (Zwipp et al., 2002; Kerkhoffs et al., 2003). The relevant literature reports (a) conflicting deductions regarding the number of degrees of freedom (DOF) of the ankle joint and (b) contradictory observations on geometry and pattern of contact of the articular surfaces, and on pattern of slackening/tightening of the ligament fibres (Leardini et al., 2000; Stagni et al., 2003). The most recent findings shows that the motion at the articulation between the inferior surface of the talus and the superior surface of the calcaneus, i.e. the subtalar joint, is considerable only when deviation forces are applied in the transverse and frontal planes but is very small in passive motion (Leardini et al., 1999b, 2001). In the latter condition, large spatial motion occurred at the tibiotalar joint apparently guided by the passive structures alone. Contact occurs at the upper articulations, medial and lateral, of the talus with the tibial mortise, also between the lateral talus and the internal distal fibula. From the intricate ligamentous apparatus which surrounds the ankle joint complex, fibres of two ligaments were demonstrated to move nearly isometrically throughout the flexion arc (Leardini et al., 1999a, b).

Despite of the large amount of experimental measurements, there are no convincing mathematical models produced. After the pioneering three-dimensional (3D) kinematic and dynamic models (Stauffer et al., 1977; Procter and Paul, 1982; Dul and Johnson, 1985), a more recent model has introduced a possible combined action of the ligaments and articulating surfaces in guiding tibiotalar joint motion, though limited to the sagittal plane (Leardini et al., 1999a). This was exploited successful for calculating ankle muscle lever arms (Leardini and O'Connor, 2002) and designing total ankle replacements (Leardini et al., 2001). Models which implied motion in 3D (Dul and Johnson, 1985), were showed later to be an oversimplification of the passive motion (Leardini et al., 1999b; Michelson et al., 2000).

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Two one-DOF spatial equivalent mechanisms for the tibiotalar joint passive motion simulation have been recently proposed by the present authors (Di Gregorio et al., 2007). The mechanisms were based on the assumption of the guiding role of the joint passive structures, such as ligaments and articular surfaces, and on their geometric dimensions. These assumed isometricity of fibres within the calcaneofibular and tibiocalcaneal ligaments and rigidity of the articulating surfaces. The latter were taken here as three sphere–plane contacts in one model, and as a single spherical pair in the other model. Although motion predicted by the models was somehow compatible with that measured in corresponding specimens, considerable differences were observed. These differences were accounted for the oversimplifications adopted to represent the complex anatomical structures and for the low efficiency of the procedures utilized at that time for mechanism dimensional synthesis.

The aim of the present study is to contribute for a better understanding of the passive 3D mobility of the tibiotalar joint with the hypothesis that this is obtained by the synergetic role of the ligaments and of the articular surfaces. A new 3D one-DOF equivalent mechanism is proposed as a model of the joint passive motion simulation. In particular, a sphere-to-sphere contact at the three articulations was considered and an accurate bone tracking system was introduced where ligament fibre isometricity was still adopted. The general approach of the previous work, i.e. experimental measurements of geometric and kinematics parameters and relevant specimen-specific model configuration, was maintained for overall consistency of the results. For a possible general improvement of the matching between model predictions and corresponding experimental measurements the following was targeted in the present study: (a) a more careful and realistic definition of the passive structures, (b) a higher number of bone position data to be analysed, and, in particular, (c) an innovative optimisation algorithm for the identification of the final mechanism geometric parameters, which result from an iterative refining process.

2. Methods

2.1. In vitro measurements

In vitro experiments were carried out to measure anatomical geometry and passive motion at the human ankle complex. Four skeleto-ligamentous lower leg preparations from lower limb amputation from four different subjects were analysed. Each specimen, including the intact tibia (Ti), fibula (Fi), talus (Ta), and calcaneus (Ca) was dissected at the Lisfranc joint line, free of all skin, subcutaneous, and muscle tissues, leaving joint capsule, interosseous membrane, and ligaments intact. A careful inspection of the specimens confirmed that they were not affected by deformations or arthritis. The tibia was fixed to an oblique arm at a horizontal workbench, with the toes upwards, whereas the other bones were left free to move (Leardini et al., 1999b; Di Gregorio et al., 2007). A pin drilled along the calcaneus longitudinal axis and protruding from the posterior surface came into contact with a rigid link, connected to the workbench by a revolute pair with axis parallel to the horizontal plane, which drove the pin to move with a five-DOF relative motion with respect to the link itself. An additional pin joined the talus to the calcaneus, forcing the subtalar joint to have no relative motion. Starting from a rest position in maximum plantarflexion, the ankle was driven to dorsiflexion by moving the rigid link up and down, until maximum dorsiflexion, thus producing flexion at the talocalcaneal segment with respect to the tibiofibular segment. Since the weight of the talocalcaneal segment and the friction between the pin and the rigid link are negligible, the motion of the talocalcaneal segment can be considered as in a virtually unloaded condition. An opto-electronic based motion tracking system (Stryker Navigation System, Stryker®, Kalamazoo, MI-USA; Freiburg/Breisgau-Germany) was used for recording the pose (position and orientation) of the two trackers, fixed to Ti and Ta according only to rigidity of the fixation and visibility of the trackers by the cameras. The camera system collected the pose of the two trackers and of the pointer in a definite workspace. The pose of the trackers was measured with respect to a Cartesian reference system fixed to the camera system while the coordinates of points measured by the pointer are given in the reference system of the relevant tracker. The specimens were further dissected and both the geometry of the articular surfaces and the insertion areas of the calcaneofibular (CaFiL) and tibiocalcaneal (TiCaL) ligaments were digitized by means of the same pointer.

2.2. The anatomical reference systems

Anatomical reference systems embedded in Ti and Ta, respectively, were defined from the anatomical landmarks measured by the pointer in the reference systems of the trackers.

In particular, the tibia–fibula anatomical reference system (S_f) was defined as follows, according to a known convention (Cappozzo et al., 1995):

- origin: located at the midpoint between the tips of the lateral and medial malleoli;
- *x*-axis: the line perpendicular to the quasi-frontal plane defined by the tips of the malleoli and the head of the fibula, and pointing anteriorly;
- *z*-axis: the line connecting the tips of the malleoli, and pointing to the right hand side of the body;
- *y*-axis: orthogonal to the previous two, according to the right hand rule.

Likewise, the talus–calcaneus anatomical reference system (S_c) was defined as follows:

- origin: located at the midpoint between the tips of the posterior ends of the lateral and medial ridges of the trochlea tali;
- *y*-axis: the line perpendicular to the quasi-transverse plane defined by these posterior tips and the head of the talus, and pointing proximally;
- *x*-axis: the line connecting the origin and the head of the talus, and pointing forward;
- *z*-axis: orthogonal to the previous two, and pointing to the right according to the right hand rule.

The 4×4 transformation matrices ${}_{F,f}T$, (which transforms homogeneous coordinates from the tibiofibular anatomical system to a reference system of the tracker on Ti) and ${}_{C,c}T$, (which transforms homogeneous coordinates from the talocalcaneal anatomical system to a reference system of the tracker on Ta) were defined. The transformation matrix ${}_{f,c}T$ from S_c to S_f was then computed by the following transformation:

$$ {}_{f,c}T = ({}_{G,f}T)^{-1} \cdot {}_{G,c}T \quad (1) $$

where S_G is the reference system fixed to the camera and

$$ \begin{aligned} {}_{G,f}T &= {}_{G,F}T \cdot {}_{F,f}T \\ {}_{G,c}T &= {}_{G,C}T \cdot {}_{C,c}T \end{aligned} \quad (2) $$

In order to define the relative orientation of Ta with respect to Ti, a sequence-independent joint coordinate system (Grood and Suntay, 1983) was adopted. The three following axes were chosen: the *y*-axis of S_f fixed to the Ti, the *z*-axis of S_c fixed to the Ta, and a floating axis defined by the cross vector product of the unit vectors of the *y*-axis of S_c and the unit vector of the *z*-axis of S_f. Three angles about these axes were defined, respectively: angle α, ankle internal(+)/external(−)

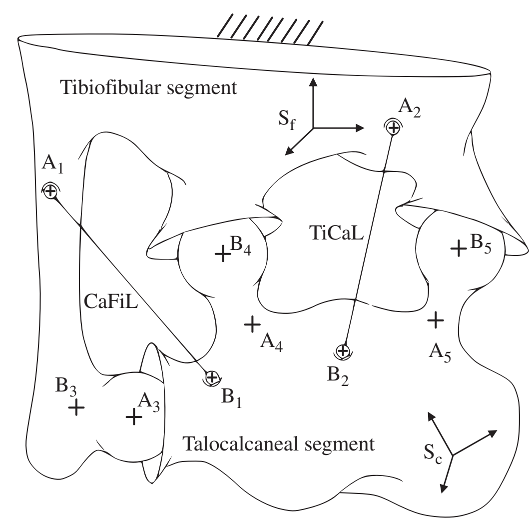

Fig. 1. A schematic generic representation of the model for the ankle joint complex.