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Verifying the equivalence of representations of the knee joint moment vector from a drop vertical jump task

Julia K. Nichols [a], Oliver M. O'Reilly [b,*]

[a] Department of Mechanical and Aerospace Engineering, University of California at Los Angeles, Los Angeles, CA 90095, USA
[b] Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA 94720, USA

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ABSTRACT

Biomechanics software programs, such as Visual3D, Nexus, Cortex, and OpenSim, have the capability of generating several distinct component representations for joint moments and forces from motion capture data. These representations include those for orthonormal proximal and distal coordinate systems and a non-orthogonal joint coordinate system. In this article, a method is presented to address the challenging problem of evaluating and verifying the equivalence of these representations. The method accommodates the difficulty that there are two possible sets of non-orthogonal basis vectors that can be used to express a vector in the joint coordinate system and is illuminated using motion capture data from a drop vertical jump task.

1. Introduction

The drop vertical jump task, Figure 1 (a), has been championed by Hewett, Myer, et al. [1] as a method to assess susceptibility to anterior cruciate ligament (ACL) injury. They have identified the knee abduction moment (KAM) during the stance phase, Stages II–IV, of this maneuver as a key predictor in ACL injury risk. The KAM, which is a specific component of the knee joint moment vector $\mathbf{M}$, is featured in numerous other studies, including gait analysis research on degenerative knee joint diseases such as osteoarthritis. The moment $\mathbf{M}$ is not measured directly, rather estimates of certain components of $\mathbf{M}$ can be computed using kinematic and force plate data with the help of software packages such as Visual3D, Nexus, Cortex, and OpenSim.

Motivated by the desire to seek clinically relevant results, one can examine multiple representations for $\mathbf{M}$ and its components (see, e.g., [2–4] and references therein). Because there is little standardization, moments are reported in the biomechanics literature in different bases. For instance, one can describe this vector using a basis fixed to the tibia, or a basis fixed to the femur, a laboratory fixed basis, or, dating to the seminal paper by Grood and Suntay [5] on the knee joint, it is also common to describe the components of $\mathbf{M}$ in terms of a joint coordinate system. If a set of Euler angles is used to describe the relative rotation provided by the joint, then each of the three joint coordinate axes can be placed in one-to-one correspondence with the axes used to define the Euler angles. This set of axes forms a set of non-orthogonal unit vectors $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ which is known as the Euler basis. In addition, associated with every set of Euler angles, a dual Euler basis $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ is also defined. Thus multiple

* Corresponding author.
E-mail address: oreilly@berkeley.edu (O. O'Reilly).

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sets of distinct basis vectors can be associated with a given joint including the orthonormal basis $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$ that corotates with (i.e., is rigidly fixed to) the proximal body, the orthonormal basis $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$ that corotates with the distal body, the Euler basis, and the dual Euler basis. By way of illustration, a representative example of the progression of the joint rotation (Euler) angles α (flexion–extension), β (adduction–abduction), and γ (internal–external rotation) through Stages II–IV of the jump maneuver is shown in Figure 1 (b) and, following O'Reilly, Sena, et al. [6], the four aforementioned sets of basis vectors axes are sketched in Figure 1 (c).

Software packages enable the output of multiple sets of components for $\mathbf{M}$. What is not apparent is how to check if the different sets of components are equivalent. This situation is particularly the case when the user has limited access to the algorithms producing the representations. Also, in order to compare results from different sources it may be necessary to transform components from one coordinate system to another. An additional complication, that has only been recently appreciated, arises because the joint coordinate system purports, not one, but two sets of non-orthogonal basis vectors: the Euler $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ and dual Euler $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ bases vectors. In this technical note, we present a straightforward method to check the equivalence of the various component representations and use experimental data from a drop vertical jump task as a demonstration. This method consists of understanding how the various components are related, how to convert between them, how to reconstruct the vector, and how to evaluate the magnitude of the vector. We also note that the results shown in this paper are the first to explicitly demonstrate that knowledge of the dual Euler basis $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ is needed to reconstruct $\mathbf{M}$ from its joint coordinate system components provided by popular biomechanics software packages.

To make this work as widely accessible as possible, a detailed discussion of the transformations between the various set of basis vectors and components can be found in the supplementary electronic resources that accompany this article. We also note that the work by Grood and Suntay [5] prompted a series of related investigations and standardizations for other anatomical joints (see [7] and [8]). Consequently, many of the methods discussed in this paper can be used with other anatomical joints such as the ankle, shoulder, and elbow joints.

2. Methods

2.1. Acquisition of sets of kinematic and force data

Participant movement data was used from a larger motion analysis study to monitor return-to-play criteria after ACL injury. The study was approved by University of California, San Francisco, Committee on Human Research (IRB 12-10253). Forty eight

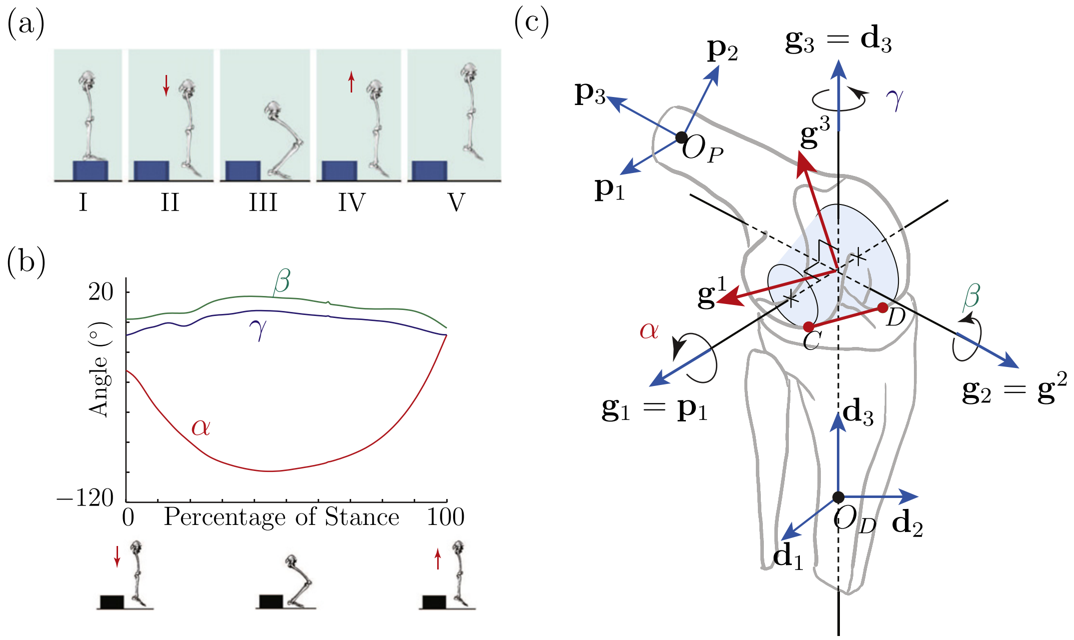

Figure 1. (a) Schematic of the five stages of the drop vertical jump task. (b) Variation in the right knee joint angles during a drop vertical jump task. The stance phase starts at initial contact, Stage II, and ends at take-off, Stage IV. (c) Schematic of the right knee joint showing the proximal $\{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3\}$ and distal $\{\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\}$ bases which corotate with the femur and tibia, respectively. The Euler $\{\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3\}$ and dual Euler $\{\mathbf{g}^1, \mathbf{g}^2, \mathbf{g}^3\}$ basis vectors associated with the rotation of this joint when it is parameterized using a set of 1-2-3 Euler angles ($1 = \alpha, 2 = \beta, 3 = \gamma$ as in Grood and Suntay [5]) and the condyles C and D are also shown.