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Propagation of the hip joint centre location error to the estimate of femur vs pelvis orientation using a constrained or an unconstrained approach

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Abstract

To estimate hip joint angles during selected motor tasks using stereophotogrammetric data, it is necessary to determine the hip joint centre position. The question is whether the errors affecting that determination propagate less to the angles estimates when a three degrees of freedom (DOFs) constraint (spherical hinge) is used between femur and pelvis, rather than when the two bones are assumed to be unconstrained (six DOFs). An analytical relationship between the hip joint centre location error and the joint angle error was obtained limited to the planar case. In the 3-D case, a similar relationship was obtained using a simulation approach based on experimental data. The joint angle patterns resulted in a larger distortion using a constrained approach, especially when wider rotations occur. The range of motion of the hip flexion–extension, obtained simulating different location errors and without taking into account soft tissue artefacts, varied approximately 7 deg using a constrained approach and up to 1 deg when calculated with an unconstrained approach. Thus, the unconstrained approach should be preferred even though its estimated three linear DOFs most unlikely carry meaningful information.

Keywords: Hip joint centre; Joint kinematics; Constraint; Degrees of freedom; Gait analysis

1. Introduction

The description of the relative movement between adjacent bony segments, that is of joint kinematics, entails the definition of a physical model of the portion of the skeletal system involved. In the model, bones are represented using rigid bodies. The pose of these bodies is described making reference to Cartesian systems of axes. For the sake of repeatability, these axes are defined using anatomical information (anatomical frames: AF). Two adjacent bones are either mutually unconstrained, thus their relative motion has six degrees of freedom (DOFs), or they are linked through a constraint characterised by a number of DOFs that, in principle, may vary between zero and five. The latter constraint can be represented by a passive mechanism that models the joint function (cylindrical or spherical joint, etc.).

The movement of the skeletal model during the execution of a selected motor task is most often reconstructed using the instantaneous position in a laboratory frame of skin markers obtained through stereophotogrammetry and bone pose mathematical estimators (motion capture). The subject-specific model parameters are determined through ad hoc experiments (anatomical calibration). When no constraint is assumed between segments (six-DOF joint), the definition of the pose of each bone requires the reconstruction of the position in the laboratory space of at least three

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non-aligned skin markers (Cappozzo et al., 1995). The latter number may be lowered if the joints are constrained (Kadaba et al., 1990, Davis et al., 1991).

Although, in principle, the unconstrained (UC) approach appears as most desirable, since it provides a complete description of the kinematics of a joint, during the joint movement, some of the DOFs may be characterised by an amplitude that is comparable with that of the errors and artefacts that affect them. Therefore, the relevant information content may be concealed (Leardini et al., 2005). In this case, rather than disregarding the data relative to these DOFs a posteriori, it may be thought plausible to sacrifice them a priori by embedding selected joint constraints while estimating the joint kinematics (constrained approach, CN). This may help either the above-mentioned economisation of the number of markers used or the redundancy of the experimental information that can be exploited for the minimisation of the propagation of experimental errors and artefacts to the reconstruction of the skeletal movement. However, one may wonder whether these benefits are jeopardised by the negative effects caused by

- the functional discrepancy between the real joint and its model, and by
- the inaccuracy with which the parameters that describe the subject-specific joint model are determined.

This paper tackles the above-mentioned problems with regard to the hip joint.

There is ample evidence that, under the normal range of motion and in able-bodied subjects, the hip joint is well described by a spherical hinge model (Dennis et al., 2001). Pathological joints may deviate from this behaviour to various extents. Despite of this, the centre of the acetabulum and that of the femoral head rarely reach distances that are greater than a few millimetres and thus greater than the inaccuracy with which they may be estimated with state-of-the-art methods (Leardini et al., 1999). Consequently, when dealing with the hip joint, the functional discrepancy between the real joint and a spherical hinge model is, normally, not a significant source of error. The centre of this hinge coincides with the centre of rotation of the femur relative to the pelvis (hip joint centre: HJC). This centre of rotation is made to coincide with the geometrical centre of the acetabulum and, in turn, with the centre of the femoral head. If the CN approach is adopted, the coordinates of this point in the pelvic AF represent the joint model parameters.

The question that remains to be answered regards the propagation of the errors that affect the HJC determination to the hip joint angles estimate as obtained using a constrained three-DOF or an unconstrained six-DOF approach.

It should be emphasised that, in both UC and CN approaches, the HJC is used to define the longitudinal anatomical axis of the femur, therefore, an error in its location affects the orientation of the relevant AF (Cappozzo et al., 1995; Wu et al., 2002). In the CN approach, the global position of the HJC is also used to reconstruct in each instant of time the pose of the femur, whereas in the UC approach this pose is reconstructed using only the global positions of thigh markers.

The issues relative to the propagation of the artefacts associated with the relative movement between markers and underlying bone (soft tissue artefacts) and with the approach that allows for its minimisation are certainly relevant, but call for a separate analysis and it is not dealt with in this paper.

2. Materials and methods

The problem was first tackled in the hypothesis of a planar motion because in this case an analytical solution was possible. Then, 3-D movements were considered using a computer-generated simulation based on experimental data.

2.1. 2-D case

In the planar case, the hip joint was represented by means of a cylindrical hinge and the kinematics was estimated using a CN (one-DOF) (Fig. 1a) and an UC (three-DOFs) approach (Fig. 1b). Through simple geometrical considerations, the joint angle estimation error, in an ith instant of time during movement, was found to be given by the following equation:

$$\Delta\alpha_i = \alpha_i - \hat{\alpha}_i = \cos^{-1}\left(\frac{1 - \frac{r}{R}\cos(\alpha_i - \varepsilon_i)}{\sqrt{1 + \left(\frac{r}{R}\right)^2 - 2\frac{r}{R}\cos(\alpha_i - \varepsilon_i)}}\right). \quad (1)$$

In the CN approach, $\hat{C}_0$ is stationary relative to the pelvis, thus ε_i is a movement-independent constant referred to as ε_0 (symbols are defined in Fig. 1a). In the UC approach, the point $\hat{C}_i$ moves with the femur and ε_i varies with α_i, but (α_i–ε_i) results in a movement-independent value equal to ε_0 (Fig. 1b).

2.2. 3-D case

In the 3-D case, a nominal data set was generated that represented the relative movement of a model of the pelvis and the femur linked through a spherical hinge.

Realistic nominal values of both parameters (anatomical landmarks) and variables (three hip angle time