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A survey of formal methods for determining the centre of rotation of ball joints

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Abstract

The determination of an accurate centre of rotation (CoR) from segment marker positions is of interest across a wide range of applications, but particularly for clinical gait analysis and for estimating the hip joint centre during surgical intervention of the knee, for limb alignment purposes. For the first time in this survey of formal methods, we classify, analyse and compare different methods (geometric, algebraic, bias compensated algebraic, and Pratt sphere fit methods, as well as the centre transformation technique, the Holzreiter approach, the helical pivot technique, the Schwartz transformation techniques, the minimal amplitude point method and the Stoddart approach) for the determination of spherical joint centres from marker position data. In addition, we propose a new method, the symmetrical CoR estimation or SCoRE, in which the coordinates of the joint centre must only remain constant relative to each segment, thus not requiring the assumption that one segment should remain at rest.

For each method, 1000 CoR estimations were analysed with the application of isotropic, independent and identically distributed Gaussian noise (standard deviation 0.1 cm) to each of the marker positions, to all markers on the segment simultaneously and the two in combination. For the test conditions used here, most techniques were capable of determining the CoR to within 0.3 cm, as long as the spherical range of motion (RoM) of the joint was 45° or more. Under the most stringent conditions tested, however, the SCoRE was capable of best determining the CoR, to within approximately 1.2 mm with a RoM of 20°. The correct selection and application of these methodologies should help improve the accuracy of surgical navigation and clinical kinematic measurement.

Keywords: Centre of rotation; Ball joints; Joint centre

1. Introduction

The determination of joint kinematics during clinical motion analysis often includes assumptions regarding the point about which two segments move relative to one another. The determination of this so-called centre of rotation (CoR) can often be difficult to measure in vivo (Cappozzo et al., 2005; Croce et al., 2005), but knowledge of its exact location is important in clinical gait analysis settings, where the calculation of hip joint moments may form the basis of therapy. In addition, the ability to establish the hip joint centre for determining lower limb alignment axes during surgical intervention (Kinzl et al., 2004) of the knee is becoming increasingly important with the increasing popularity of navigation systems, with accuracy a premium.

Although specific bone landmarks and joint positions can be measured using techniques such as digital roentgen stereophotogrammetric (Vrooman et al., 1998) and video fluoroscopy analysis (Dennis et al., 1998), reflective marker positions determined using infra-red optical systems allow non-invasive measurement of kinematics in real time. During gait analysis or surgery, such markers may be fastened to the skin or more directly attached to the bone segments. The CoR at the hip may then be calculated from the three-

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The conditions used in this study (marker configuration, error conditions, segment movement etc.) should be seen as only a typical example for demonstrating the accuracy of each of the various approaches. With, e.g. a different number of markers, different marker placement or configuration, it may be entirely possible to achieve a more accurate joint position. Specific techniques may therefore offer further enhancement of the accuracy of the approaches investigated in this study by optimising the configuration and position of markers within the sets. The conditions chosen in this study, however, allowed a complete and fair comparison between the different methods. Furthermore, the relative performance of the different approaches investigated in this study is almost independent of the test conditions. If the specific conditions were known prior to a practical application, it could be that the optimal method of CoR determination can be chosen for those conditions. Although highly unlikely, it may be that certain applications require the determination of a CoR when one segment is rigidly fixed. Under such circumstances, the use of the geometric, bias compensated algebraic or Pratt sphere fit techniques may be justified. Under more normal conditions for kinematic assessment, but also in the operating theatre where it is almost impossible to hold one segment stationary relative to the global measurement system, the use of the SCoRE has here been shown to yield the best results. This method has the benefit that it is fast and just as, or more simple, to implement as any of the other techniques. It also has the distinct advantage that the position of the joint centre is provided in both of the local segment coordinate systems.

For the first time, a complete survey and classification of formal methods has been performed in this study. A new method, the SCoRE, has additionally been presented, for which no assumption of the segment movements relative to the CoR is required. In nearly all test scenarios investigated in this study, the SCoRE produced the smallest errors in the estimation of joint centre. Follow-up work to this study involves similar direct comparisons to be performed on clinical data.

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