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A procedure to estimate the origins and the insertions of the knee ligaments from computed tomography images

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ABSTRACT

The estimation of the origin and insertion of the four knee ligaments is crucial for individualised dynamic modelling of the knee. Commonly this information is obtained *ex vivo* or from high resolution MRI, which is not always available. Aim of this work is to devise a method to estimate the origins and insertions from computed tomography (CT) images. A reference registration atlas was created using a set of 16 bone landmarks visible in CT and eight origins and insertions estimated from MRI and in vitro data available in the literature for three knees. This atlas can be registered to the set of bone landmarks palpated on any given CT using an affine transformation. The resulting orientation and translation matrices and scaling factors can be used to find also the ligament origin and insertions. This procedure was validated on seven pathological knees for which both CT and MRI of the knee region were available, using a proprietary software tool (NMSBuilder, SCS srl, Italy). To assess the procedure reproducibility and repeatability, four different operators performed the landmarks palpation on all seven patients. The average difference between the values predicted by registration on the CT scan and those estimated on the MRI was 2.1 ± 1.2 mm for the femur and 2.7 ± 1.0 mm for the tibia, respectively. The procedure is highly repeatable, with no significant differences observed within or between the operators ($p > 0.1$) and allows to estimate origins and insertions of the knee ligaments from a CT scan with the same level of accuracy obtainable with MRI.

1. Introduction

The main role of the ligaments, which connect bone with bone, is to provide mechanical stability to the joints, guiding their movements and preventing excessive motion. The knee is the largest and complex joint of the human body and has four major ligaments: Medial Collateral (MCL), Lateral Collateral (LCL), Anterior Cruciate (ACL) and Posterior Cruciate (PCL). In clinical applications and biomedical research individualised musculoskeletal models are currently used for many purposes such customised prosthetic implants (Bert, 1996; Reggiani et al., 2007), computer-aided surgery (Zanetti et al., 2005), gait analysis (Kepple et al., 1997) or automated image segmentation (Ellingsen et al., 2010). In orthopaedic surgery a geometric model of the patient's bone can reproduce the basics morphometry in order to perform a correct computer based surgery (Radermacher et al., 1998). In gait analysis an accurate geometrical model is fundamental to create a realistic musculoskeletal model (Kepple et al., 1997).

Many computational dynamic models of the knee have been developed (Arnold et al., 2010; Blankevoort and Huiskes, 1996; Guess et al., 2013; Kia et al., 2014; Shelburne and Pandy, 2002) to understand the forces and the strains on the knee structures, such as the ligaments, during static and locomotion activities. Improving the accuracy of these models could help to discover the causes of ligaments' injury and guide the surgical treatment in order to improve the functional outcome (Woo et al., 2006). A subject specific model of the knee is also essential for total knee arthroplasty in the preoperative phase in order to assure the durability and the reliability of the joint implant especially for younger patient with a greater physical activity (Zanetti et al., 2005). The accurate estimation of the origin and insertion of these ligaments is a crucial step in all the above applications.

Subject specific models of the knee can be generated using information obtained either *ex vivo,* probing fresh cadavers, or from high resolution Magnetic Resonance Imaging (MRI). Brand et al. (1982) used measurement on three cadavers to obtain a set of lower extremity origin and insertion coordinates. These procedures are complex and cumbersome, therefore many studies utilised a few

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number of specimens, limiting the impact of the findings. In addition, the data obtained from cadavers have proven to be valid for modelling the knees they have been acquired for, but may likely not translate to other subjects (Bloemker et al., 2012). Many studies proposed methods to create subject specific model by scaling a generic template in order to measure inaccessible point such as the origin and insertions of the knee ligaments (Brand et al., 1982; Lewis et al., 1980). This procedure, that involves the scaling of a generic template, provides one cloud of palpable points on a cadaver specimen and corresponding points on the in vivo subject. Calculating the transformation between these two landmark clouds allows measuring inaccessible points.

The parameters needed to determine a rigid body transformation are a rotation matrix, a translation vector and a scaling factor. Lew and Lewis (1977) demonstrated that the application of data obtained from cadavers directly to an in vivo subject is not suitable, scaling is required because of the dimension differences between the in vivo subject and the cadaveric specimens. Morrison (Morrison, 1970), in order to study the mechanics of knee joint in relation to normal walking, developed a technique to scale uniformly along the axes bony landmarks from dry bone data and an experimental subject. Lew and Lewis (1977) formulated a scaling technique that includes the Morrison method to scale inaccessible points from a dried bone specimen to an in vivo subject. This technique provides anisotropic scaling along three mutually orthogonal axes defined in both rigid bodies and is based on the use of four landmarks palpable on the subject and four on the corresponding specimen. The landmarks used to determine the rigid body transformation will contain some errors that come from the palpation of those points on the reference specimen and the experimental subject. Challis (Challis, 1995) suggested a procedure using a linear least-square method which attempted to take into account those errors. Unfortunately, this method allows the calculation of the rigid body transformation parameters assuming that the scaling is uniform along the three axes. Anisotropic scaling technique has been presented by Lewis et al. (1980), using eight landmarks on both the specimen and the experimental subject, the results revealed that the anisotropic scaling was more accurate than the isotropic scaling.

In view of all that has been mentioned so far, it can be said that previous studies validated procedures that allow calculating inaccessible points on in vivo subjects using different osteometric scaling techniques. In these studies the analysis of human subject in vivo has been performed without using CT (computed tomography) or MRI scan images. Since only a minimal set of skeletal landmarks can be palpated through external palpation, the number of the landmarks used in the previous methods was very low. Lewis et al. (1980) demonstrated that anisotropic scaling improves the identification of anatomical landmarks locations, particularly when a large number of points were used in the scaling. Also, a detailed description of the landmarks selected was not present in the previous studies, the lack of standard and well defined guidelines for the palpation of the these landmarks affects the accuracy of the rigid body registration (Van Sint Jan and Della Croce, 2005).

The purpose of this study was to create a procedure to estimate the origins and the insertions of the knee ligaments by: providing a reproducible and repeatable anatomical landmark cloud for virtual palpation, and creating a registration atlas and using an affine transformation (rotation, translation, anisotropic scaling). The accuracy of this procedure will be assessed through comparison with results obtained from MRI.

2. Materials and methods

The dataset used in this study (D1) has been provided by Medacta International SA (Castel S. Pietro, Switzerland). It consists of seven set of images obtained from seven different patients (64 ± 5 years) who have undergone a Total Knee Replacement. Each patient's dataset includes CT and MRI of pathological knee that underwent surgery and the bone geometries obtained by segmenting the CT data. In addition to D1, a second dataset (D2) has been obtained from the multibody models of the human knee project (Guess et al., 2013, 2010; Bloemker et al., 2012). These models are based on three cadaver knees (Table 1) that have been mechanically tested in a dynamic knee simulator. Knee geometries (bone, cartilage and menisci) were derived from MRI and ligament insertions were obtained from both MRI and probing the cadaver knees. D2 also contains information on ligament modelling, including the origin and insertion locations Fig. 1.

The first part of this study aims at creating a reproducible and repeatable bone landmarks cloud to be palpated on CT scan images. A detailed standard description of body landmarks through manual or virtual palpation is available in literature (Van Sint Jan, 2007). Among these, a subset of landmarks (see Fig. 2) belonging to the knee, tibia and fibula has been chosen. This landmark cloud has then been identified on each subject dataset through virtual palpation. NMSBuilder (http://www.nmsphysiome.eu/resources.html , SCS srl, Italy) has been used to visualise the 3D geometry and to perform the virtual palpation (location of anatomical points over a 3D visualisation) and the registration between the landmark clouds. The virtual palpation has been performed by four expert operators on both D1 and D2. Each operator performed the virtual palpation on ten knees (cases), repeating the operation three times for each knee (trials). Three operators performed the procedure using NMSBuilder, whereas the fourth one used an in-house tool developed by Medacta International SA. Reproducibility and repeatability were assessed using repeated measures analysis of variance (ANOVA). In particular, a repeated measure ANOVA was performed for each operator considering the “case” as between group factor and the “trial” (3 levels) as within factor. Three separate ANOVA, one for each test, were then performed considering the operator as between group factor and the cases as within group factor (10 levels).

Once reproducibility and repeatability of the bone landmarks had been assessed, they were palpated on D2 in order to create a reference landmark cloud (C_R), and on D1 in order to create a subject-specific landmark cloud (C_S). Once palpated, the two clouds had to be registered. An affine transformation was used to this purpose. The method that allows the calculation of the parameters that describe an affine transformation between two paired landmark clouds is called, in statistical shape analysis, *Procrustes Analysis* (Grimpampi et al., 2014). In particular, the affine transformation that maps C_R to C_S is composed by a 3×3 transformation matrix, which includes Translation ($T = T_x, T_y, T_z$), Rotation ($R = R_x, R_y, R_z$), and scaling ($S = S_x, S_y, S_z$) parameters. This operation is implemented in Lhp Builder following the method proposed by Horn (Horn, 1987). Once T, R and S are calculated, it is possible to register on C_S also those landmarks belonging only to C_R, which, in our case, are the origins and insertions of the four knee ligaments. The ensemble of C_R and of the eight origins and insertions of the knee ligaments composes the so-called Registration Atlas (RA). The error associated to the registration procedure is called Procrustes Distances (PD) and represents the geometric distance between C_S and C_R. These values estimate the accuracy of the procedure.

The scaling operation, necessary to take into account anthropometric differences due to age or gender (Fehring et al., 2009), might have as a consequence the fact that landmarks in C_R are not always located on the bone surface. For this reason, a visual inspection needs to be performed after the registration and adjustments need to be taken. These adjustments were performed using an ad-hoc Lhp Builder function, names “snap to surface”, which allows to move the landmark along the axes characterised by the minimal distance from the closest surface. The repeatability of this operation has been assessed by having one operator repeating it for three times on each case in D1 (after having performed the calculation of the origins and insertions of the knee ligaments using the RA, as described in the following paragraph).

Using the three models from the D2 dataset, four atlases were created: one for each model and one as the average of the previous three (Atlas 1, Atlas 2, Atlas 3 and Atlas M). Not having a proper gold standard available, the four atlases have been compared in terms of Procrustes Distance between the landmarks of C_R registered on the subjects and the landmarks of C_S palpated on the seven subjects.

Once the best RA had been selected, it was used to estimate the origin and the insertions of the knee ligaments of all the cases in D1. Initially, the origin and insertions were calculated through the affine transformation using the CT scan, successively the verification of the positions of those landmarks has been performed using MRI scan where it was possible to estimate the ligaments attachments. In NMSBuilder, the landmarks that represented the origins and insertions of the ligaments were moved whenever the position was considered wrong in according with those images. Then, we compared the distances between the data obtained from the CT scan with those corrected with MRI.

Table 1
Characteristics of the D2 donors.

	Age at death (years)	*Gender*	*Right or Left*	*Height (m)*	*Mass (Kg)*
Knee #1	*77*	*Male*	*Right*	*1.77*	*99*
Knee #2	*55*	*Female*	*Left*	*1.70*	*72*
Knee #3	*78*	*Female*	*Right*	*1.65*	*58*