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SCR: A METHOD FOR REMOTE MEASUREMENTS OF LIGAMENT STRUCTURE

R.C.M.B. Meijer*+, R. Huiskes*, J.M.G. Kauer+

*Dept. of Orthopaedics, Biomechanics Lab., and
+Dept. of Anatomy and Embryology,
University of Nijmegen, P.O.Box 9101,
6500 HB Nijmegen, The Netherlands.

Introduction

Essential for mechanical analyses of ligaments and tendons is a quantitative description of the collagen structure. The present paper introduces a non-destructive and remote method to determine the geometry and the superficial fiber orientation of ligaments and tendons.

The method is called SCR (Stereophotogrammetric Curve Reconstruction) and uses principles of traditional photogrammetry. Huiskes et al. (1985) emphasized the advantages of close range photogrammetry for surface shape reconstruction, in the sense that all the necessary information can be rapidly recorded after preparation, whereafter the specimen can be discarded. The surfaces are not touched during the measurements, so no local damage or deformation can occur.

The development of SCR for ligaments and tendons is based on the observation, that ligaments consist of individual fibers, with an almost parallel course between the insertions. The method itself and its application to ligaments are discussed here.

Methods

The SCR method is similar to traditional stereophotogrammetry in the sense that it uses photographic exposures of the object and a calibration cage taken from two sides. Whereas object points are reconstructed in traditional stereophotogrammetry, SCR reconstructs an object curve, such as a ligament fiber.

Considered is a curve K, projected from two camera stations F and G on the fiducial plane (fig. 1). For any point C" of the projected curve K", there exists at least one point C' of K', so that their projection lines intersect. The intersection, belonging to C" and C' is the original C.

In traditional stereophotogrammetry, the points C" and C' must be identified and measured directly from the exposures. In the present case, the projected curves on both exposures are digitized individually, in an arbitrary sense. For every point C" on K", the computer program will select two points A' and B' on K', which define the curve section on which C' must be located. This section is linearized, and the spatial plane FA'B' is reconstructed. Intersection of projection line GC" with this plane delivers an estimate of the position of the original C. By scanning K" from beginning to end, a full description of the curve is obtained.

Evidently, the equation system determining the estimated position of C is ill-conditioned if the angle between the projection line GC" and the plane FA'B' is small. This is the case, when the angle between A'B' and the line through the camera stations is small. For that reason, it can be necessary to make a second filmpair for a certain setup with the pair of cameras a quarter turn rotated around an axis perpendicular to the fiducial plane.

Error Analysis

Apart from well known error sources in the photogrammetry (Huiskes et al., 1985) due to lens distortions, unflatness of fiducial and photographic image planes, calibration and digitizing, the SCR method introduces a reconstruction error as well.

Any estimate R of a point C is not a point on the curve K, if R' is not a point of the curve K' (Fig. 2). The reconstruction error is $\varepsilon = \| \underline{c} - \underline{r} \|$, where $\underline{c}$ and $\underline{r}$ are the vectors describing the positions of C and R in a laboratory coordinate system, respectively.

Suppose u'_m is the maximum distance of the curve K' from the straight line segment A'B', then $\varepsilon = Ju'_m$, whereby J depends on the experimental setting (camera positions and object position relative to the fiducial plane), and the orientation of A'B' in the fiducial plane. Fig. 3 shows a schematic configuration of cameras, fiducial plane and object. Normally the object is close to the fiducial plane, here it is schematized as lying in the fiducial plane. The angle α indicates the local direction of K'. In this case J remains small over a large range of α, ($J < 2.0$ for $\alpha > 30°$), but increases to infinity, if α tends to zero, indicating coplanarity of K', G and F. Hence, not only for the ill-conditioned equation system for the reconstruction, but particularly to avoid large reconstruction errors, it is necessary to have a second filmpair with the cameras a quarter turn rotated available.

Application to Ligaments

In a pilot experiment the fiber structure of the medial side of an anterior cruciate ligament of a right pig knee was measured.

The capsule, collateral ligaments, the posterior cruciate and the menisci were removed. By a sagittal cut through the femur the medial condyl was removed to get a clear view at the anterior cruciate. Synovial and loose tissue was removed.

The femoral and tibial ends were fixed in a rig with six degrees of freedom, allowing a search for the position of the bones, whereby all the fibers of the ligament were tightened without the application of high forces.

A considerable problem in applying this technique is the quality of the photographic exposures. Polarization filters, several different film types, light angles and camera angles were tried in order to optimize the technique in such a way, that adequate contrast was obtained to make the fiber structure visible on multiple exposures. An example of one of the exposures is shown in fig. 4.

Six exposures were made from different angles. The fiber curves, as far as visible, were digitized with a precision of 20 μm (Huiskes et al., 1985). Reconstructions of the digitized photographs are shown in fig. 5. These reconstructions include the contours of the femoral condyl, tibial plateaus and the femoral cutting surface, which are not used for the actual 3-D reconstruction.

Eight filmpairs were assembled to reconstruct as many curves as possible. Figure 6 shows the reconstructed ligament, with the local fiber orientation indicated.

Discussion

The SCR method is also suitable to measure and describe spatial surfaces without a natural fiber structure. In this case, lines are drawn or projected on these surfaces. Because of the arbitrary scanning method, a variable sample density can be used, in order to reduce the reconstruction errors where radii of curvature are high. Advantages of SCR over traditional stereophotogrammetry in measurements of joint surfaces (Huiskes, et al., 1985) are easy indentification of object lines and a faster data-acquisition procedure. The application of the SCR method to ligaments requires a thorough experimental technique where optimization of photographic quality is crucial. The pilot study showed that SCR can be an effective, non-destructive tool to measure ligament-fiber orientation, which has not been possible as yet with any other method.

References

Huiskes, R., Kremers, J. de Lange, A., Wolting, H.J., Selvik, G. and van Rens, Th.J.G. "Analytical stereophotogrammetric determination of three-dimensional knee joint geometry". J. Biomech. Vol. 18, pp 559-570, 1985.

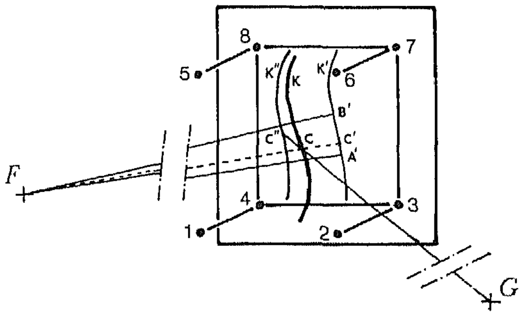

fig. 1 Schematic drawing, elucidating the method. The points 3, 4, 7 and 8 of the calibration cage represent the fiducial plane.

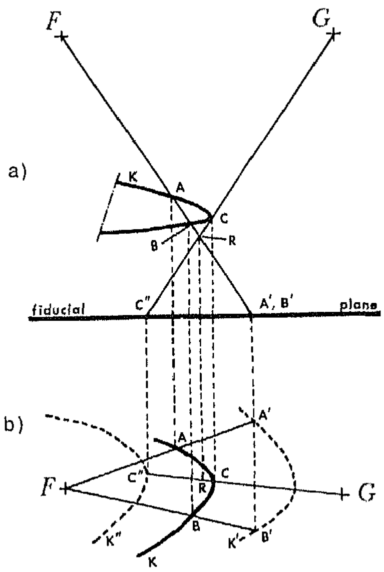

fig. 2 The position of the intersection R of (i) the plane through the camera station F and the points A' and B' of the projected curve K', and (ii) the line through the camera station G and the point C" of the projection K";
a) side-view,
b) top-view.

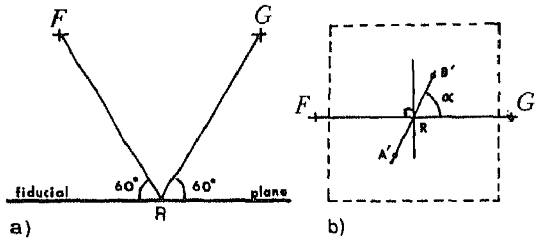

fig. 3 A typical experimental setting,
a) side-view,
b) top-view.

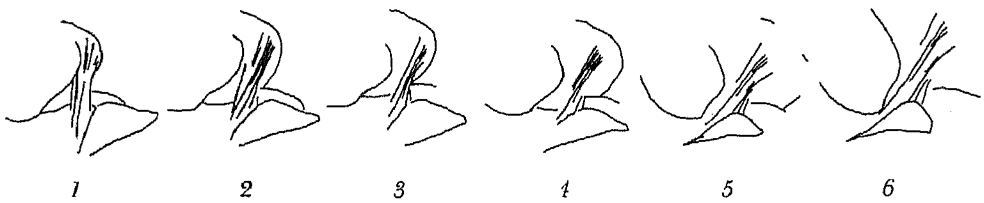

fig. 5 Six plots showing the ACL photographs in digitized form.

fig. 4 Detail of photograph no. 4 of the six ACL photographs.

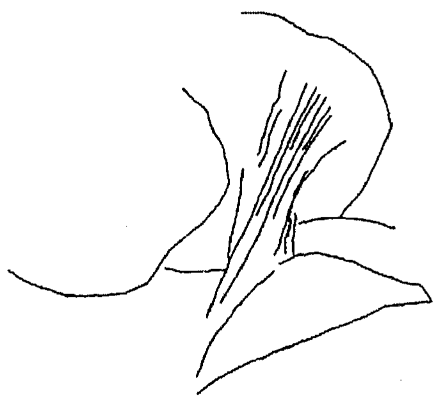

fig. 6 The reconstruction of the ACL, plotted in photograph no. 4.