

Technical Note

Instantaneous moment arm determination of the cat knee

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Abstract

The moment arm is an important parameter for calculating forces and pressures at a joint. Present techniques described in the literature are limited for joint studies in animals because of the invasive procedures required which destroy the joint integrity. This paper describes a new application of the instantaneous helical axis (IHA) for determination of the moment arm of the knee joint without compromising its integrity. Measurements based on the IHA technique are compared to an established technique using six cadaveric cat hind limbs. One experiment using the IHA technique was performed to demonstrate its application *in situ*. It was found that the moment arm determined by both techniques resulted in continuous estimations of similar magnitudes over the expected range of motion of the knee joint, although the IHA technique is sensitive to smoothing. A trend toward increasing moment arm as a function of increasing knee angle was observed in four of six specimens. The *in situ* experiment demonstrated the ability to use the IHA technique without compromising the integrity of the knee joint so that further histological, morphological, or topological information could be investigated. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

A moment arm is defined as the perpendicular distance between the line of action of a muscle or tendon and the joint axis of rotation (e.g. Spoor et al., 1990). It is useful for the calculation of joint torques and internal joint contact forces (Ronsky, 1994), it can also give insight into the function of a joint (Young et al., 1993). In animal joint injury models there are often both mechanical and biological changes associated with an injured joint. Therefore, it is advantageous to measure the moment arm without compromising the integrity of the joint so that further histological, mechanical, and topological measurements can be made.

There have been several techniques reported in the literature for measuring moment arms. A comprehensive review and evaluation of these techniques was presented by An et al. (1984). The measurement techniques reviewed can be divided into three general categories: geo-

metric methods (e.g. An et al., 1981), tendon displacement methods (An et al., 1983; Brand et al., 1975; Spoor et al., 1990), and direct load measurement methods (e.g. Ketchum et al., 1978). The disadvantage of many of these techniques is that they require specimen dissection resulting in loss of joint integrity which limits further analysis. A more recent technique uses magnetic resonance imaging (MRI) for determination of moment arms of intact human joints (Rugg et al., 1990; Spoor et al., 1990). However, MRI is presently limited due to high cost, the limited number of measurements possible at discrete knee angles, and the difficulty of application to small joints due to limited resolution.

The instantaneous helical axis (IHA) method describes joint motion in terms of a rotation about and a translation along a helical axis (Woltring et al., 1994). The IHA is a three-dimensional axis of joint rotation and its position may vary as a function of joint angle. Combining the knowledge of both the joint axis of rotation using the IHA with the measured three-dimensional line-of-action (LOA) of the tendon, the moment arm can be estimated as the common perpendicular distance between the two (Fig. 1).

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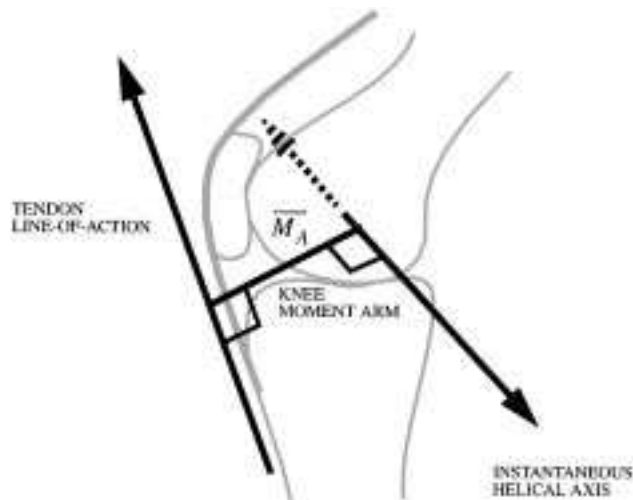


Fig. 1. The moment arm ($\|\vec{M}_A\|$) of the knee is the common perpendicular distance between the instantaneous helical axis (IHA) and the tendon line of action (LOA).

The purpose of this study is to demonstrate the suitability of this new application of the IHA technique for the determination of joint moment arm calculations in a cat knee joint while retaining the integrity of the joint for subsequent biological measurements. Moment arm measurements are calculated with the IHA technique and are compared with the tendon excursion method (e.g. Spoor et al., 1992). Practical application of the IHA technique is demonstrated with an *in situ* determination of moment arm.

2. Methods

Six cadaveric cat hind limbs (3.1 ± 0.7 kg) were used in this study. For each limb, the IHA moment arm data was collected first, then the tendon excursion data. This order was consistent for all limbs because joint integrity is not maintained after the tendon excursion protocol. Finally, an experiment was performed to demonstrate the practical use of the IHA method *in situ*. All aspects of animal care and experimental procedures were approved by the University of Calgary Animal Care Committee.

The six fresh frozen hind limbs were severed at the proximal end of the femur and fixed in a rigid clamp so the knee joint could freely move from 40° to 140° knee angle (Fig. 2a). Two marker arrays with four markers each were mounted on the femur and tibia. Markers in each array were distributed isotropically to accurately define the rigid body motion description (Challis, 1995). Two flat round markers mounted on the proximal and distal ends of the exposed patellar tendon defined the tendon LOA. A video-based motion analysis system (Expert Vision, Motion Analysis Corporation, Santa Rosa, CA) consisting of four digital cameras (240 Hz) was used

to collect the three-dimensional kinematic marker position data (RMS = ± 80 μ m in x, y, and z estimated from a static trial) during 10 repeated trials of continuous leg movement from maximum flexion to maximum extension. The passive motion was induced by manually pulling on the quadriceps muscle group and each cycle took an average of 1.5 s. For each specimen, ten repeated trials were performed to determine repeatability of the moment arm measurements. An additional ten trials were conducted with a $+5^\circ$ (medial) and -5° (lateral) deviation from the quadriceps LOA (0°) to test the IHA technique sensitivity to the direction of quadriceps pull. The one *in situ* experiment followed a similar protocol to the cadaveric experiment, except the quadriceps were activated by electrical stimulation of the instrumented femoral nerve (Herzog et al., 1992; Ronsky et al., 1995). The kinematic data was smoothed with quintic splines at an effective Butterworth cut-off frequency of 3 Hz (GCVSPL package; Woltring, 1986).

Detailed theoretical background and method for determining the IHA is described by Berme et al. (1990) and Woltring et al. (1994). Determining the three-dimensional position of the IHA at each sampling time interval for subsequent moment arm calculations requires determining the angular velocity vector ($\vec{\omega}$), which indicates IHA orientation and magnitude, and the axis position vector ($\vec{\rho}_n$) which locates the IHA in the reference coordinate system. The vector $\vec{\rho}_n$ is a function of the velocity ($\vec{\mu}$) of the point on the rotating body instantaneously coincident with the origin of the fixed frame:

$$\vec{\rho}_n = \vec{\omega} \times \vec{\mu} / \|\vec{\omega}\|^2.$$

In calculating $\vec{\omega}$, the rigid body motion as a function of time with respect to a stationary neutral trial in the lab coordinate system (lcs) was determined for the tibia (${}^{lcs}R$ and ${}^{lcs}\vec{d}$) and the femur (${}^{lcs}R$ and ${}^{lcs}\vec{d}$) (Söderkvist and Wedin, 1993), and subsequently the relative rotations, ${}^fR$, and displacements, ${}^f\vec{d}$:

$${}^fR = {}^{lcs}R^T \cdot {}^{lcs}R,$$

$${}^f\vec{d} = {}^{lcs}R^T ({}^{lcs}\vec{d} - {}^{lcs}\vec{d}).$$

The relative rotations and displacements were differentiated using a three-point finite difference algorithm to obtain ${}^f\dot{R}$ and ${}^f\dot{\vec{d}}$, respectively (Woltring et al., 1994). Finally, a skew-symmetric matrix (S) was calculated (Berme et al., 1990) from which the angular velocity, $\vec{\omega}$, is extracted.

$${}^fR^T \cdot {}^f\dot{R} = S(\omega) = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$

$$\Rightarrow \vec{\omega} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}.$$

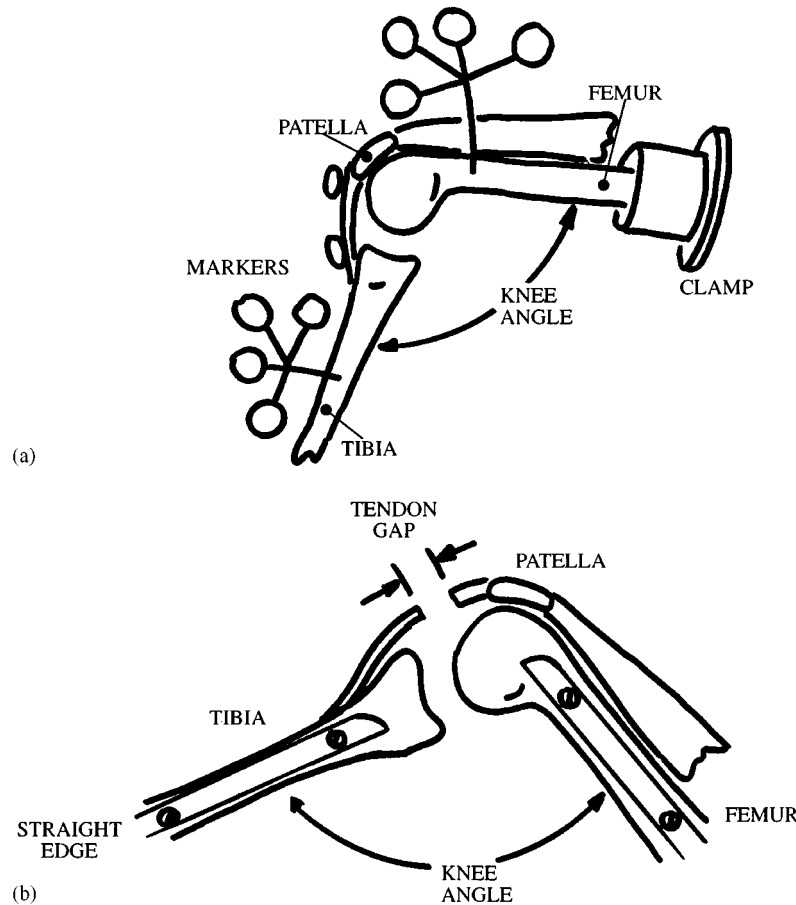


Fig. 2. Schematic of experimental setups of knee joint for (a) instantaneous helical axis technique, and (b) tendon excursion technique. Straight edges mounted on the tibia and femur are used to define the knee joint angle. Knee angle is defined as the inside angle between the tibia and femur.

The three-dimensional unit vector representing the IHA ($\bar{i}ha$) has the direction $\bar{\omega}$ and passes through $\bar{\rho}_n$. Further clarifying, any point $\bar{p}$ on the IHA can be written as $\bar{p} = \bar{\rho}_n + \bar{\omega}\alpha$ for some scalar α . The direction of the tendon LOA is represented by a three-dimensional vector ($\bar{l}oa$) passing through the two markers on the patellar tendon surface, offset by half the tendon thickness. The moment arm ($\|\bar{M}_A\|$) is the magnitude of the common perpendicular between the $\bar{i}ha$ and $\bar{l}oa$ vectors:

$$\|\bar{M}_A\| = \frac{1}{\|\bar{l}oa \times \bar{i}ha\|} \|(\bar{l}oa \times \bar{i}ha) \cdot \bar{v}tv\|$$

where $\bar{v}tv$ is a three-dimensional vector connecting an arbitrary point on IHA with an arbitrary point on LOA.

The tendon excursion technique (Spoor et al., 1990) was adapted from the work of Hasler (1996). The hind limb was embalmed (10% formaldehyde) for 24 h with the leg fixed in full extension. The fixation stiffens the soft tissues which allows reliable measurements of the tendon gap. The patellar tendon was transected at the mid-section, and a series of 12 sagittal plane photos (Fig. 2b) were taken at finite steps of approximately 5° increments

from 150° to 60° of decreasing knee angle (flexion series), and then 12 more photos were taken as the leg was fully extended in 5° increments (extension series). The joint angle and tendon gap were digitized from the photos, smoothed (0.5 Hz) using quintic splines (An et al., 1983; Spoor et al., 1990), and the derivatives were determined to calculate the moment arm as a function of joint angle.

3. Results

The mean and standard deviation (SD) of the moment arm determined with the IHA technique for each cadaveric specimen (10 trials each) were determined as a function of joint angle between 70° and 150° knee angle. For the same joints, the moment arms determined by the tendon excursion method for the flexion and extension series of data showed magnitudes quantitatively similar to those determined by the IHA technique (Fig. 3). Both techniques determined the moment arm within the bounds of knee angles that a cat knee joint operates during normal activities (Goslow et al., 1973). There is a trend toward increased moment arm as a function of

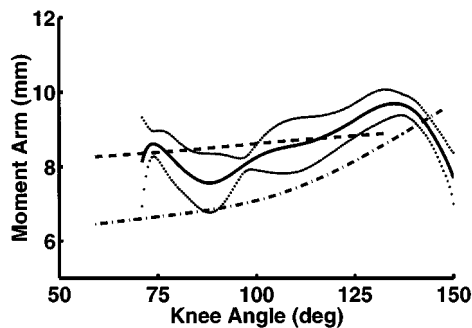


Fig. 3. Comparison of the moment arm vs knee angle of a typical cadaveric specimen using both the IHA technique (mean, solid line; S.D., dotted line) and the tendon excursion technique (extension series, dashed line; flexion series, dash-dotted line).

increased knee angle, although this was consistent for only four of six cadaveric specimens. The decreased tendon excursion moment arm calculated with the flexion series of data is due to a lower rate of tendon excursion as a function of knee joint angle than for the extension series of data.

There was no substantial difference in the IHA moment arm in the cadaveric specimens when the quadriceps pull deviated medially or laterally ($\pm 5^\circ$) from the estimated quadriceps LOA. This indicates that the IHA results for the cadaveric specimens are not sensitive to small deviations of the quadriceps LOA while being manually pulled.

The IHA moment arm length determined in the *in situ* experiment for ten trials were averaged and the SD determined between knee angles of 70° to 120° (Fig. 4). The reduced range of knee angles was due to the inability to track the marker data collected past 120° due to non-optimal camera placement. The standard deviations of the IHA moment arm determined for the *in situ* experiment were less than all cadaveric experiments.

4. Discussion

The IHA is a differential quantity which makes it sensitive to landmark position errors (Woltring et al., 1985). Therefore, the IHA moment arm results are sensitive to the degree of smoothing selected for the tibia and femur landmark position data. Ideally, an objective method of determining the smoothing factor for these data would be preferred, however Woltring et al. (1994) showed that the GCV optimum did not result in the minimal IHA dispersions, and typically undersmoothed the data (de Lange et al., 1990; Woltring et al., 1985). An alternative objective method was attempted using the estimated RMS of these data. However this also undersmoothed the data. A subjective approach was the most successful where the smoothing factor was chosen by

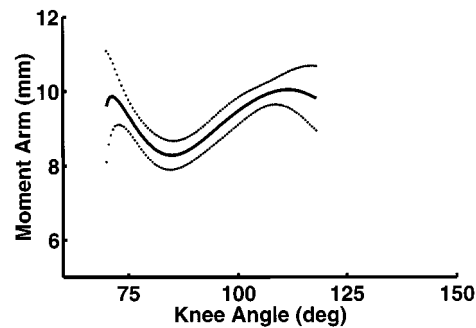


Fig. 4. Moment arm vs knee angle using the IHA technique of an *in situ* specimen (mean, solid line; S.D., dotted line).

a visual inspection of the fit of the splines to the raw positional marker data with the criterion that the important signal component of the joint motion was retained while the noise component was smoothed over. Interestingly, the final smoothing factor chosen corresponded to the *ad hoc* criteria suggested by Woltring et al. (1994) to select five times the fundamental frequency. Although a limitation of the IHA moment arm technique is that an objective smoothing criterion could not be employed, the subjective method resulted in reasonable estimations.

The IHA technique provides a highly sampled (360 points) measurement of the moment arm over the range of motion of the knee joint based on the mean and SD of ten repeated trials for each specimen. These results compare well with the tendon excursion measurements (Fig. 3), although this technique resulted in two different moment arms due to hysteresis between the flexion and extension data which has been observed by other authors (An et al., 1983, 1984; Hasler, 1996; Spoor et al., 1990). This is caused by the tearing of the soft tissues fixed in formaldehyde during the initial flexion series of data. Differences in the IHA moment arm between flexion and extension motions were not found because joint integrity is not compromised by the procedure. The less variable estimate of the moment arm using the tendon excursion technique compared to the IHA technique may be attributed to a smaller number of sampled data points (12 points) over the range of motion.

A characteristic of the IHA is that the position and direction errors are inversely proportional to the angular velocity which approaches zero ($\|\dot{\theta}\| \Rightarrow 0$) at the extremes of joint motion and results in poorly estimated moment arms at these extremes (Fig. 4). Furthermore, the IHA is sensitive to the three-dimensional movement patterns (Woltring et al., 1994) which are reflected in the higher variability and magnitude of the SD as a function of joint angle in the cadaveric specimens (Fig. 3) compared to the *in situ* specimen (Fig. 4). Motion patterns are more repeatable in the *in situ* experiment due to the muscular contraction of the quadriceps group around the knee induced by electrical stimulation. Although the cadaveric

results provided reasonable moment arms compared to the tendon excursion method, more repeatable measurement with the IHA technique can be achieved over the range of joint motion with *in situ* experiments.

The IHA technique is a new method of measuring the knee joint moment arm that holds various advantages over previous techniques described in literature. These include the high number of samples measured during a continuous motion, measurements from repeated trials that are averaged to determine error bounds, and, most importantly, it can be calculated *in situ* over the range of knee joint motion while maintaining the integrity of the joint for subsequent joint analysis.

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