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Instantaneous centre of rotation in human motion: measurement and computational issues

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Abstract. The instantaneous centre of rotation plays an important role in biomechanical modelling and physical-medical interpretation of human gestures. Therefore, we consider its measurement, based on video-image acquisition and processing of human motion records. Measurement and computational aspects are discussed, including the evaluation of measurement uncertainty and the estimation of the effect of some influence quantities on the determination of the position of the instantaneous centre of rotation.

1. Introduction

Modelling of human movement is often based on a multi-bodies systems, where the bodies represent human limbs. Such bodies are linked by "joints" that either represent anatomic articulations or interactions with external entities, as in the case of foot contact with ground.

Since the motion of a rigid body is characterised, at each time instant, by an instantaneous centre of rotation (ICR), its explicit measurement may be very useful in some cases.

In our experience, we have recognised three main such cases.

One case concerns the identification of the centre of a rotational joint, for placing a marker corresponding to it. This may be relatively easy, when an external anatomical landmark is available (as the malleus for the ankle joint) or quite difficult, as in the case of hip [1]. In such cases the centre of the joint may be indirectly measured as the ICR of the relative motion [2].

Another important case, is when the relative motion in the joint is not purely rotational, as it happens, e.g., in the knee. In such cases, the ICR measurement may constitute a noteworthy improvement, in respect of assuming, as a simplifying hypothesis, a simple rotation. Such an improvement may be sensible, both from the biomechanical and the clinical standpoint [3].

Lastly, the case in which the joint represents an external contact point needs also consideration. Consider, for example, the case of hopping in place: in the landing phase, the foot tip touches ground, than it starts rotation around an ICR located somewhere in the lower toes surface, and then it moves toward the metatarsus and stabilises around it, when the foot toes lie completely on the ground. In the take-off phase, after a preliminary loading, we have the opposite movement toward foot tip [4-7].

In this paper, we consider two methods for ICR calculation, the Reuleaux technique and the rigid-body approximation, particularly convenient for on-line calculation and suited for clinic investigation [8-10]. To assess their performance, we have carried out a comparative evaluation of their performance in simulated and experimental situations. In reporting on such evaluation, we present a biomechanical application regarding ICR involved in a pedalling leg. Lastly, we summarize the results of the study and provide guidelines for uncertainty reduction and evaluation.

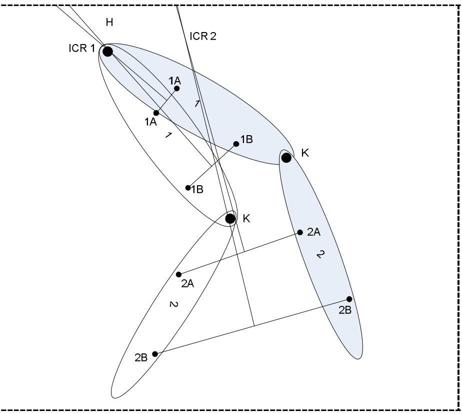


Figure 1. Lower limb scheme with two rigid bodies and hinge joints (H: hip, K: knee). Two successive positions are presented (not in scale), together with the segments connecting specific (marker) points on the segments. Perpendicular lines used to determine ICR are indicated. The ICR of the first body corresponds to H, while that of the second body results from the combination of the two rotations.

2. The instantaneous centre of rotation in biomechanics

Let's introduce briefly the concept of ICR. For the sake of simplicity, let us consider the case of planar movement of a two dimensional rigid body (Figure 1). At a specific time, ICR is the point on the plane considered around which the rigid body is rotating in that specific moment. Consequently, the ICR position generally moves in time according to rigid body motion [11-12].

This trajectory is rather intuitive in simple cases. For example consider the moving centroid for ICR corresponding to the hip when pedalling on a stationary bike. This is schematised in Figure 1 by body 1. As a first approximation, we can assume the femur (body 1) in pure rotation around the hip, fixed in a point on the saddle. Actually, from the biomechanical point of view, we could be interested in the small femur ICR movements in vertical direction, since a pelvis translation downward helps in pedalling. Beside that, hip articulation is of difficult identification on body skin, so H point position is difficult to be measured directly and an ICR measurement is required.

In biomechanics the measurement of human body kinematics is of fundamental importance: kinematic experimental data are the base for all further computation required to determine internal moments and forces and for ICR measurements also. A proper approach consists in a video-based measurement system, including a set of markers placed in specific points of interests along the body segments investigated, a video recording system and an image processing software. As a result it is possible to obtain positions, in the two or three dimensional space, of the set of points selected and individuated by markers. Measurement is affected by influence effects: camera resolution limits the spatial measurement resolution, illumination and image contrast affect accuracy in marker identification, while the frame rate corresponds to the sampling frequency. All such issues contribute to measurement uncertainty [15].

Beside that, it is worth noting that for particular gestures or in cases in which a simplified modelling is required, a planar motion reconstruction could be sufficient, for example when dealing with pedalling on a fixed bicycle. Figure 2 shows the positions of a set of markers placed on a cycling subject, when the motion is investigated in the sagittal plane.

3. ICR measurement methods

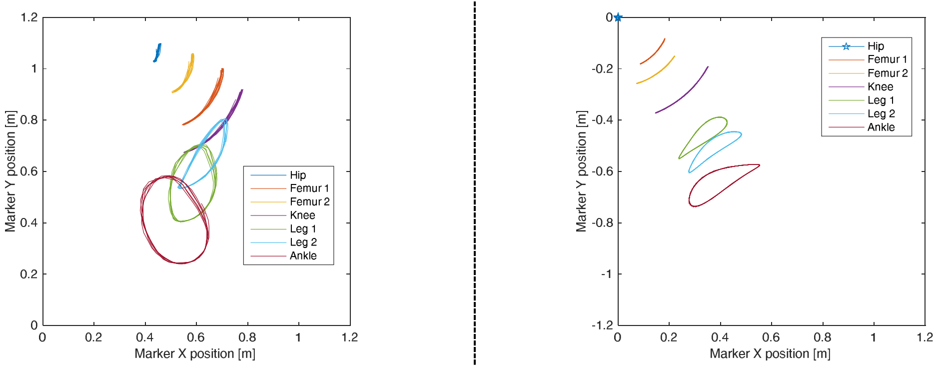
Kinematic experimental data constitute the input for ICR measurements, together with a multi-body model of the limbs under investigation. Usually positions of a cluster of markers on each segment are measured in time, in this case we will consider minimum of two markers along each segment. A few ICR measurement methods are available in literature [14], including the one deriving from the classical mechanics method of Reuleaux [11]. This method is relatively simple, but it sometimes present inconsistencies [6].

Let us briefly introduce it. Consider a limb constituted by two rigid bodies connected by a hinge joint, as represented in Figure 1. Two points on each segment are identified by letters A, B and we consider their positions at time t_i and t_{i-1}. The main hypothesis is that at each time the movement of a rigid body can be reconstructed as a rotation around an ICR. So we can consider the segment connecting the two successive positions of each point as the cord of circumference arch actually connecting the same points. The center of such circumference is the ICR and it is located on the line perpendicular to cord segment going through its middle point. If the body is rigid and kinematic measurement traces several points on it, it is possible to identify, in the same time interval, several perpendiculars. ICR position is determined at their intersection, as presented in Figure 1.

A possible alternative is offered by point velocity, since at each time t_i point position is measured by video system and its velocity can be evaluated by, e.g., a Savitsky-Golay interpolation [15]. In this case the ICR is located at the intersection of lines perpendicular to point velocities at each time. In the following we will consider the two alternatives, since they show important differences.

As a result, in Figure 1, body 1 ICR is located on the fixed joint (hip), while body 2 ICR position is moving due to the combination of two rotations at hip and knee. In fact, body 2 ICR will suffer from error propagation as we will demonstrate in the following.

Pure translation is another important issue since it will produce an ICR located at infinity. On the other hand a combination of linear translation and rotation will move the ICR. This is particularly interesting when linear translation is due to the behavior of the joint under investigation.



a b

Figure 2. (a) Markers trajectories for the pedalling leg experiment. 7 markers are considered: 2 on femur and lower leg respectively, plus 3 on the joints: hip, knee and ankle. (b) Rigid body assembly used for synthetic data production.

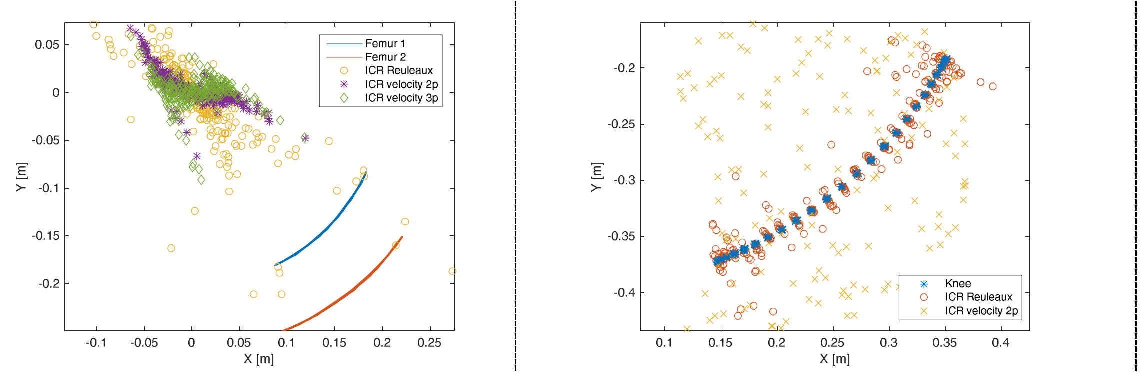
4. Experimental set up and results

Our investigation is focused on the influence of measurement noise, chord length and pure translation on ICR measurement methods presented in Section 2. For this purpose, we will use both synthetic and experimental data.

Synthetic data are useful to evaluate the processing techniques required to determine ICR under controllable reference conditions. It is possible to obtain synthetic kinematic data of a set of rigid bodies connected by pure revolute joints, with the first ICR fixed or subject to a controllable linear translation. Beside that we can vary relative angular velocities and sampling frequencies and introduce some noise if required. Figure 2b presents the situation of two bodies with 5 markers each moving with different angular velocities, while experimental data are referred to a practical biomechanical application to a pedalling leg (Figure 2a).

4.1. ICR from synthetic data

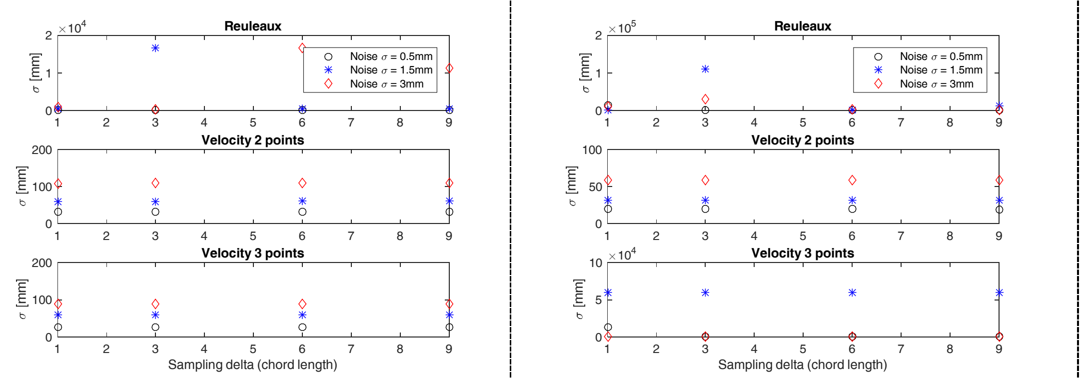
First of all the processing procedure has been validated through the use of synthetic data.



a b

Figure 3. ICR trajectories for body one (a) and two (b)

Figure 3 presents the ICR evaluated for the two bodies as presented in Figure 2a. The large ICR variability is evident in particular in the second body case. To understand the causes of such large variability, we have varied some computation parameters. ICR measurement results depend on several parameters; in particular we have investigated the following: - random Gaussian noise affecting position measurements;- length of the chord used for ICR computation; - number of points involved in the procedure. Concerning Gaussian noise we have considered a noise standard deviation of 0.5-1.5 and 3 mm. These are representative of a good experimental setup, a normal one and a difficult image processing situation. The chord length a parameter connected to rotational velocity of the segment and sampling frequency. Since we have a fixed sampling frequency, we have varied the time step between points used for ICR computation: i and i+1 or i and i+3, i and i+6 and i and i+9. Finally a minimum of two points on a rigid segment are required for computation: we have considered the possibility to use two or three points, as it may happen in practice.



a b

Figure 4. Standard deviation of ICR position (x) for body one (a) and two (b) as a function of chord length and noise levels, for the three methods considered.

Figure 4 presents ICR results standard deviation as a function of the chord for the three noise levels considered and the three methods: Reuleaux and velocity based on two or three points. It is evident that velocity methods present more stable results when varying the chord length. As regards Reuleaux method, in this case a computation using points i and i+6 gives the lowest variability. Table 1 presents some numerical figures. It is worth noting that usually systematic deviations of mean values from nominal values are limited, while in some cases very high variability is observed. Beside that, it is evident that the uncertainties propagate toward the second body for which we have a larger variability.

Table 1. Noise effect in ICR measurements for synthetic signal at different noise levels and a mean chord length

			Hip			**Knee**	
			Reuleaux	**Velocity 2p**	**Velocity 3p**	**Reuleaux**	**Velocity 2p**
Noise σ=0.5mm	**σ [mm]**	X	20.2	32.9	26.0	22.6	19.9
		Y	23.6	17.9	22.3	0.5	8.9
Noise σ=1.5 mm	**σ [mm]**	Y	457	60.5	59.2	520	31.4
		X	389	83.3	75.8	1.9	9.2
Noise σ=3 mm]	**σ [mm]**	X	1650	110	88.9	3100	58.7
		Y	1540	117.7	93.6	6.4	21.5

4.2. Biomechanical application

Let’s consider now the pedaling leg for which markers trajectories presented in Figure 2 are obtained at 25 Hz frame rate with a spatial resolution of about 3.5 mm (standard deviation about 2mm). In this case it is clear that the marker that was intended to be placed on the hip is misplaced along the femur since it presents some movement. For this reason ICR measurement is fundamental to identify hip position. Since the subject is cycling seated on the saddle in a first phase we can imagine a fixed ICR or hip, but results will be affected by a hip translation also due to pelvis contribution.

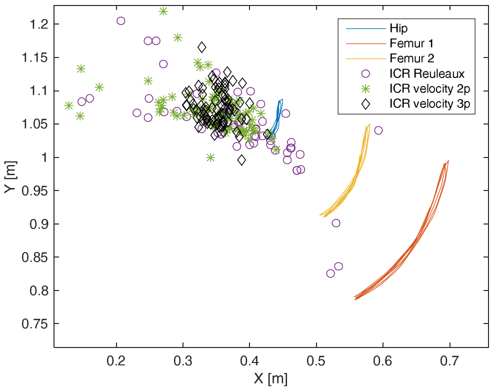


Figure 5. Pedalling leg example: trajectories for three femur landmarks and their ICR computed with the three methods considered.

Figure 5a presents femur ICR in the fixed reference frame. Considering a fixed hip we can evaluate mean value and standard deviation, which is about 35 mm. According to the synthetic case similar deviations may appear with a random noise with a sigma between 0.5 mm (σ=25 mm) and 1.5 mm (σ=65 mm), confirming a good accordance with the practical biomechanical example. Beside that a contribution due to translation is certainly present. In such cases synthetic data demonstrate by far a larger deviation (100% increment as compared with pure rotation at the same noise level), confirming difficulties in evaluating ICR when a translation contribution is present. Such problems are much more evident when dealing with the second rigid element ICR (as depicted in par 4.1). In this case, beside noise and joint translation, there is certainly a contribution due to markers motion on subject’s skin during pedaling. Since all the considered methods rely on the hypothesis of rigid bodies, this seems to be the cause for the unreliable results obtained for knee ICR.

5. Conclusions

We have investigated some aspects in ICR position measurement, based on kinematic experimental data. Several issues have been addressed: noise influence, sampling or frame rate frequency, number of markers involved, presence of a translation contribution. In order to establish a controllable reference situation, synthetic data were produced by a simulator. It was possible to establish ICR measurement methods performance under controllable conditions. The velocity method has proved to be more reliable in presence of noise, in particular when three markers are involved in the procedure. When a translation is added, ICR measurement is very critical above all when dealing with the second segment in a two degrees of freedom system. We obtained some useful indication for the variability of the results and its dependence on noise and chord length or sampling rate. The velocity method has demonstrated a very good stability with both noise and chord length variations, as compared with the original Reuleaux's method. Nevertheless, when dealing with the second body in a chain, uncertainties are very large and results become unreliable in the practical application considered. In this case some further investigation is required to confirm that a violation of the rigid body hypothesis causes unpredictable ICR position deviations, and to determine if there are feasible countermeasures to limit such effects, when processing the results.

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