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Optimising filtering parameters for a 3D motion analysis system

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ABSTRACT

In the analysis of movement data it is common practice to use a low-pass filter in order to reduce measurement noise. However, the choice of a cut-off frequency is typically rather arbitrary. The aim of the present study was to evaluate a new method to find the optimal cut-off frequency for filtering kinematic data. In particular, we propose to use rigid marker clusters to determine the dynamic precision of a given 3D motion analysis system, and to use this precision as criterion to find the optimal cut-off frequency for filtering the data. We tested this method using a model-based approach in a situation in which measurement noise is a serious concern, namely the registration of the kinematics of swimming using a video-based motion analysis system. For the model data we found that filtering the data with a single cutoff frequency of 6 Hz under some conditions decreased the accuracy of the reconstruction of the kinematics compared to using the unfiltered data. If the cut-off frequency was used that yielded optimal dynamic precision, then the accuracy improved by 29% compared to using raw data irrespective of the cluster position, close to the optimal accuracy improvement of 30%. We confirmed in an experiment that the cut-off frequency at which optimal precision was found varied between cluster positions and subjects, similar to the results obtained with the model. We conclude that 3D motion analysis systems can be made more accurate by optimising the cut-off frequency used in filtering the data with regard to their precision. Furthermore, the dynamic precision method seems useful to evaluate the effect of various filtering procedures.

1. Introduction

Motion analysis is widely used to study human motor behaviour. As measurement noise is inevitable, it is common practice to low-pass filter the kinematic data in order to reduce the effects of measurement noise. If the relevant frequency content of the raw signal is known, then numerous methods are available to distil the relevant signal. However, in movement analysis it is often unknown which part of the frequency content represents the actual movement. In that case, the experimenter has to choose an appropriate filtering procedure, and decide what cut-off frequency should be chosen in this procedure. Using a high cut-off frequency removes only very little noise, whereas a low cut-off frequency will introduce artefacts in the trajectory.

Bartlett (2007) stated that cut-off frequencies between 4 and 8 Hz are often used in filtering movement data. In most studies, the arguments for choosing a particular smoothing procedure and cut-off frequency are not specified, even though several quantitative measures have been proposed to objectively determine the optimal filtering procedure (Corradini et al., 1993; Cappello et al., 1996). These measures are based on the difference between the filtered and raw data. An alternative for optimising filtering in case the relevant frequency spectrum is unknown, which has not been recognised and investigated before, is to use the resulting precision of the 3D motion analysis system in question as a criterion for finding the optimal filtering frequency. We investigated the merits of this new *dynamic precision method* in the kinematic analysis of underwater swimming, where high-precision motion analysis systems with active markers based on infrared technology, such as Optotrak®, cannot be used due to the aquatic environment and passive, video-based systems have to be used instead. Moreover, experimental set-ups for underwater 3D reconstruction using video cameras (e.g. Ceccon et al., 2013; Silvatti et al., 2013) were found to be less precise compared to values obtained above water (Ehara et al., 1995). Therefore, underwater environments represent a context where optimising precision is of particular concern.

The precision of motion analysis systems is usually assessed under either static or dynamic conditions. In static conditions, the average deviation in the reconstruction of non-moving marker

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coordinates from the known positions is taken as a measure of accuracy. In dynamic conditions, precision is determined by calculating the variation in distance between two or more markers fixed on a rigid body moving through the calibrated volume (Haggard and Wing, 1990). Since movement analysis systems are used to reconstruct movements, the precision in dynamic conditions is more important than in static conditions. Ideally, precision should be determined during the registration of the movement of interest itself (e.g. swimming). As far as we know, however, no study to date has determined the precision of a motion analysis system in this manner. Here, we will test whether this dynamic precision method yields a filter frequency that corresponds to the one that optimises filtering. This can be done using any set of filters; in the present study we will use it to determine the optimal filter frequency of a Butterworth filter.

Quantifying underwater motion is important in the study of swimming because, as in many other sports, technique is considered one of the most important factors for achieving a good performance. Technique has been studied mostly by determining temporal and spatial characteristics of the stroke (e.g. Suito et al., 2008; Rouard, 2011). Some authors have examined arm trajectories in relation to the generation of propulsive force (e.g. Schleihauf, 1979; Berger et al., 1995) and performance level (e.g. Deschodt, 1996). However, as pointed out by Ceccon et al. (2013), the majority of kinematic studies do not provide a full description of joint kinematics in terms of Euler angles. This might be related to the poor visibility of bony landmarks during the stroke and the complex calculations that are needed to convert kinematic data to Euler angles. To determine segment orientations, additional technical markers on the skin of the subject may be used, a method called the Calibrated Anatomical System Technique (CAST) (Cappozzo et al., 2005). Recently, Ceccon et al. (2013) were the first to employ this technique in swimming research. They concluded that the use of additional technical markers led to an increase in the percentage of video frames in which segment positions and orientations could be determined.

In the present study, technical markers were not only used for good visibility in the video captures, but also to determine the dynamic precision of the movement registration used by placing the technical markers as rigid body clusters on the segments. In particular, we employed actual swimming data and simulations with added measurement noise to determine the dynamic precision of a bout of movement registration, and subsequently used this precision to optimise filter frequency. For each rigid body (with several markers attached to it), we determined how dynamic precision depended on the filter frequency, and determined the frequency (f_{dp}) that yields optimal dynamic precision of the resulting movement registration. We obtained similar results for both model and experimental data. We used the model simulation to check that f_{dp} corresponded to the cut-off frequency that optimised the accuracy.

2. Methods

2.1. Model

We used a model of the swimming movement (corrupted by measurement noise) to establish to what extent the filter frequency at which optimal dynamic precision was achieved improved accuracy (i.e. improved reconstruction of the uncorrupted trajectory). The model of Payton et al. (1997) incorporates the movement of the trunk and arm to simulate the front crawl movement in swimming. It was used to study swimming kinematics and is therefore suitable to address the current research question. The model (see Fig. 1) consists of the following segments: trunk (half width: Q to S), upper arm (S to E) and forearm/hand (E to H). By supplying the angle-time profiles for the body roll angle (θ), shoulder abduction angle (α), elbow flexion angle (β) and shoulder extension angle (ϕ), in combination with the trunk midpoint position Q, the kinematic data of the swimming movement can be generated.

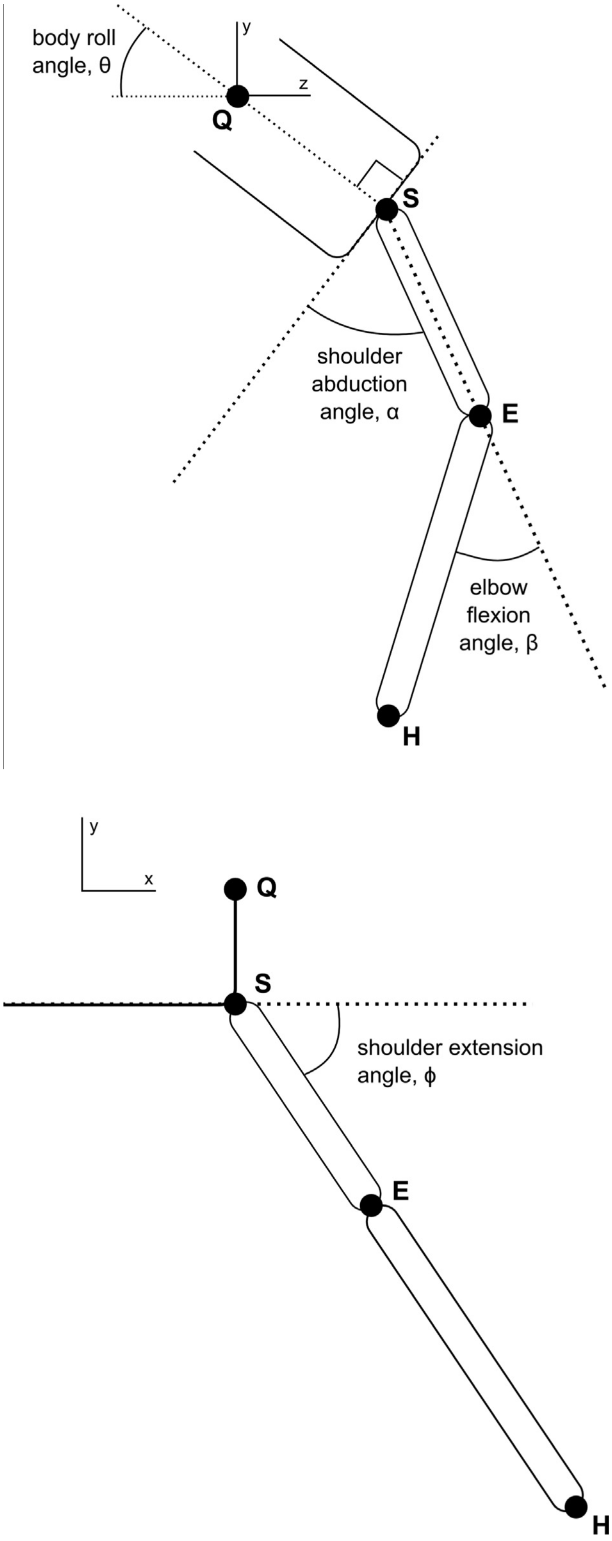

Fig. 1. Kinematic model viewed from behind (top) and from the side (bottom).