# Kinematics estimation using a global optimization with closed-loop constraints

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## INTRODUCTION

The global optimization of a chain model has shown many interests to estimate the joint kinematics: the mediolateral rotation of the thigh is improved [2], the data are directly usable for simulation [1] and the kinematics can be accurately reconstructed using a small number of markers or marker occlusions [1]. The reconstruction is feasible while the Hessian matrix remains of full rank. For some activities (*e.g.* kayaking and rowing) the number of degrees-of-freedom (*dof*) is reduced due to closed-loops; in this case fewer makers should be required or the redundancy should increase the accuracy of the reconstruction.

The purpose of this study was to compare a standard algorithm of global optimization with a new algorithm with closed-loop constraints to reconstruct a paddling kinematics.

## METHODS

A kayaker performed setup movements for locating the joint centres using a functional approach [3] and six trials of paddling on an ergometer. The kinematics were acquired using a 10-camera motion analysis system at 300 Hz (T40, Vicon - Oxford, UK). A 17-segment, 42-*dof* chain model was developed in the *HuMAnS* toolbox and its parameters (i.e. segment lengths and marker locations with respect to the respective body segment) were determined using 94 reflective markers.

Three marker sets (A, B, C) shown in Fig. 1 ($n_A$=88, $n_B$=46, $n_C$=29 markers) and two algorithms of global optimization were used to reconstruct the joint kinematics. The first one (*algo1*) corresponded to a Newton–Gauss non-linear least square algorithm. The configuration $\mathbf{q}$ was iteratively adjusted $(\mathbf{q}=\mathbf{q}+d\mathbf{q})$:

$$\begin{cases} \min\limits_{dq} \frac{1}{2} d\mathbf{q}^{\mathrm{T}} \mathbf{J}^{\mathrm{T}} \mathbf{J}\, d\mathbf{q} + \left[\mathbf{J}^{\mathrm{T}} \left(\mathrm{Tags}(\mathbf{q}) - \mathbf{T}_{obs}\right)\right]^{\mathrm{T}} d\mathbf{q} \\ \mathbf{q}_{\min} - \mathbf{q} \le d\mathbf{q} \le \mathbf{q}_{\max} - \mathbf{q} \end{cases} \quad (1),$$

where $J_{i,j} = \dfrac{\partial \mathrm{Tags}_i(\mathbf{q})}{\partial q_j}$ for $i$=1…$n$ and $j$=1…42.

The second algorithm (*algo2*) was based on a quadratic programming with a weighting matrix and constraints to ensure the closed-loops of the lower-limbs (feet strapped on the footrest) and the upper-limbs with the paddle. The constraints $\mathrm{Task}(\mathbf{q})$ were introduced on the augmented Jacobian matrix

$$\mathbf{J}_A = \left[ \mathbf{J} \;\vdots\; \frac{\partial\, \mathrm{Task}(\mathbf{q})}{\partial\, \mathbf{q}} \right]^{\mathrm{T}}:$$

$$\begin{cases} \min\limits_{dq} \frac{1}{2} d\mathbf{q}^{\mathrm{T}} \mathbf{J}_A^{\mathrm{T}} \mathbf{W} \mathbf{J}_A\, d\mathbf{q} + \left[ \mathbf{J}_A^{\mathrm{T}} \mathbf{W} \begin{pmatrix} \mathrm{Tags}(\mathbf{q}) - \mathbf{T}_{obs} \\ \mathrm{Task}(\mathbf{q}) \end{pmatrix} \right]^{\mathrm{T}} d\mathbf{q} \\ \mathbf{q}_{\min} - \mathbf{q} \le d\mathbf{q} \le \mathbf{q}_{\max} - \mathbf{q} \end{cases} \quad (2).$$

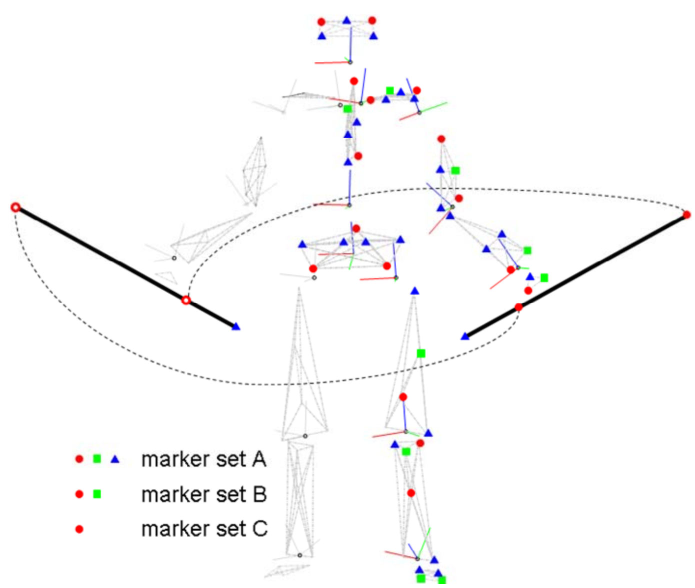


**Figure 1**: Paddler model with the three marker sets. The markers on the right limbs are similar to those on the left limbs. Two half-paddles are modeled with two markers that should coincide.

The global error of reconstruction was calculated as:

$$E = \frac{1}{F}\sum_{f=1}^{F}\sqrt{\frac{1}{3\times N_f - 42}\sum_{n=1}^{N_f}\left(\mathrm{Tags}(\mathbf{q}) - \mathbf{T}_{obs}\right)^2},$$

where $F$ is the number of frames and $N_f$ the number of visible markers for frame $f$.

The kinematics reconstructed using all the markers and *algo1* was the reference and root mean square differences (RMSd) were calculated between the reference and the other kinematics for the upper-limbs, lower-limbs and trunk *dof*.

## RESULTS AND DISCUSSION

Fig. 2 shows an example of the reconstruction of the initial posture and the error in location between the observed markers and those obtained by the optimal chain model configuration.

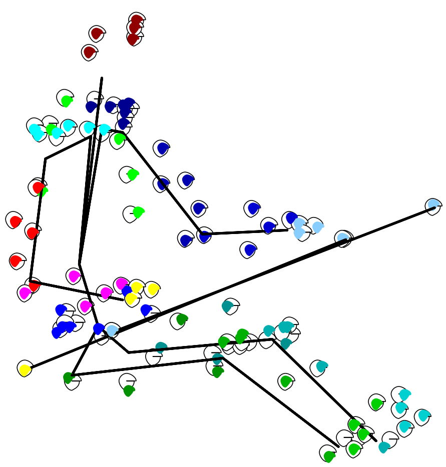

**Figure 2** The dots represent the observed markers and the circles are the markers associated with the chain model.

The standard algorithm did work with the marker set *C* because the Hessian calculated as $\mathbf{J}^T\mathbf{J}$ in Eq. (1) was not of full rank. The ankle *dof* could not be determined because no marker was on the feet. The other combinations algorithm-marker set gave a mean error of about 10 mm (Table 1).

**Table 1:** Reconstruction error (in meters)

| Marker set | A | B | C |
|---|---|---|---|
| *algo1* | 0.010 | 0.010 | -- |
| *algo2* | 0.008 | 0.011 | 0.016 |

With the decreased redundancy, the kinematics is less smooth because the random errors (e.g. skin movement artefact) are not compensated for; moreover the RMS difference increased (Table 2). With marker set B (46 markers for a 42-*dof* model), the RMS difference was up to 3º. This difference was slightly modified by the closed-loop constraints (*algo2*B *versus* *algo1*B). The RMS difference increased of 3º when 17 additional markers were removed.

**Table 2:** Root mean square differences (in degrees) [upper-limbs, lower-limbs, trunk+head]

| | A | B | C |
|---|---|---|---|
| *algo1* | reference | [2.1, 2.3, 2.5] | -- |
| *algo2* | [1.7, 0.2, 0.1] | [3.4, 2.1, 2.5] | [6.2, 4.0, 4.8] |

The markers were removed from an *a priori* knowledge of the skin movement artefact. Further analyses will be performed to select the minimal marker set that minimizes the RMS differences.

This study helps in determining a minimal marker set for on-water experiments (in a towing tank) where the kayaker will be followed by a moving motion analysis system [4]. In this case a limited number of markers can be reconstructed because (*i*) the lower-limbs and the pelvis are partially hidden in the boat and (*ii*) the 3D reconstruction will be less accurate than a reconstruction in laboratory conditions due to vibrations and water reflections. The marker set *C* composed of a few markers (e.g. no marker on the feet, the back of the pelvis) placed as far as possible to each other took into account these limitations. The second algorithm highlights that closed-loop constraints can be introduced in a global optimization to improve the reconstruction of the joint kinematics.


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