LOWER LIMBS AND PELVIS CONTRIBUTIONS IN KAYAK PEFORMANCE A COMPUTER SIMULATION STUDY

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INTRODUCTION

The kinematics analyses in kayaking were focused on the upper limbs and the trunk [1-2]. The lower limbs and the pelvis were considered as links between the upper limb that produced the drive force and the boat.
Swivel seats recently appeared to increase the pelvis rotation caused by asymmetrical movements of the lower limbs. This rotation increases the paddle range of motion and its velocity. As the drive force is mainly dependent on the antero-posterior (x) velocity of the paddle tip, changes in paddle kinematics modify the performance.
The purpose of this study was to determine the contribution of both the pelvis and the lower limbs in the kayaking performance from a kinematics driven simulation. The contribution was expressed in terms of paddle tip velocity and impulse of force.

METHODS

Experimental part

A kayak ergometer was designed using a static frame on which a trolley (*i.e.* footrest and seat complex) moved back and forth. A bungee cord linked the back of the frame with the trolley. An air brake simulated the water drag on the blade. The paddle was linked to the air brake by two ropes. The contact forces of the system "*athlete-paddle-trolley*" were forces applied on the paddle tips (λ_2 and λ_3) and the tension of the bungee cord linking the trolley to the frame (λ_1). Three uniaxial force sensors measured these contact forces.

Twelve elite kayakers paddled on a sliding ergometer. They performed three trials of 60 seconds at 69, 84 and 92 strokes per minute. Four markers were placed on the pelvis and the shoulder and five additional markers defined the trolley, the paddle tips and the ropes kinematics. The length of the segment was measured in line with the anthropometrical model of Zatsiorsky modified by de Leva [3].

Numerical part

The model "ergometer-kayaker-paddle" [4] was implemented under *HuMAnS* [5]. The dynamics was represented as Lagrangian dynamics with Lagrange multipliers for introducing the contacts forces:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \hat{\mathbf{o}} + \mathbf{C}^T\ddot{\mathbf{e}} \quad (1)$$

where the vectors $\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ represent the generalized coordinates, their velocity and acceleration. $\mathbf{M(q)}$, $\mathbf{N}(\mathbf{q},\dot{\mathbf{q}})$ and $\mathbf{G(q)}$ are the inertia matrix, the other inertial nonlinear effects (Coriolis and centrifugal forces) and the gravity effects, respectively. The vector $\boldsymbol{\tau}$ represents the joint torques and $\mathbf{C}^T\ddot{\mathbf{e}}$ the contact forces.

The kayaker-paddle-trolley model was composed of 18 bodies (Figure 1). 22 degrees of freedom described the kayaker movements ($\mathbf{q1}=[q_1..q_{22}]^T$), 6 represented the trolley kinematics ($\mathbf{q2}=[q_{23}..q_{28}]^T=[0\ 0\ 0\ q_{26}\ 0\ 0]^T$) and 3 more were necessary for the air brake. Due to the numerous contacts with the trolley and the paddle, there were two closed-loops.

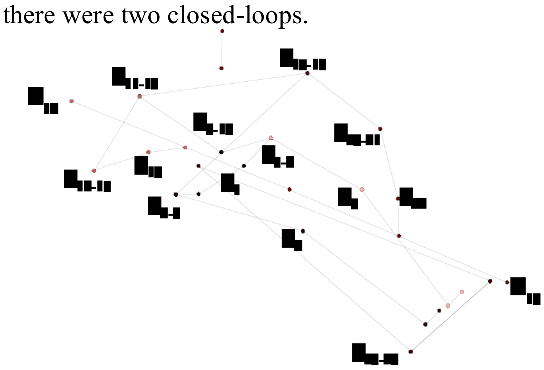

Figure 1: Schematic diagram of the system "athlete-trolley"

The simulation was driven by the kinematics of paddling tasks: the paddle trajectory and the pelvic and scapular girdle's rotation. The generalized co-ordinates were calculated by solving an inverse kinematics problem. The redundancy was solved by introducing a damped pseudo-inverse of the Jacobian ($J_{i,j}= \partial x_i/q_j$) and an optimization term to keep the joint angles as far as possible to the joint limits.
The acceleration of the trolley could be expressed according to the state variables, the kayaker's anthropometric model [3] and the dynamics of the air brake that was modelled from measurements with a torque sensor [4]. The ordinary differential equation was solved with root finding under *Scilab* to handle the events in the air brake dynamics: *i.e.* the left or right ropes could (or could not) drive the flywheel.

From all the trials, 26 kinematics tasks were fitted by Fourier series with one harmonic. Then two simulations were performed. The first [**C1**] was obtained by considering the pelvis rotation. In the second [**C2**], the pelvis was fixed before solving the direct dynamic problem. The difference between [**C1**] and [**C2**] is due to the pelvis and lower limbs kinematics.

From the state variables in [**C1**], the instantaneous contribution of each part in the antero-posterior component of the paddle right tip velocity was calculated:

$$\dot{T}_{14}^x = \underbrace{\frac{\partial T_{14}^x}{\partial q_{1-7}}\dot{q}_{1-7}}_{Lower\ \mathrm{limbs}} + \underbrace{\frac{\partial T_{14}^x}{\partial q_{8-10}}\dot{q}_{8-10}}_{Trunk} + \underbrace{\frac{\partial T_{14}^x}{\partial q_{11-22}}\dot{q}_{11-22}}_{Upper\ \mathrm{limbs}} + \underbrace{\frac{\partial T_{14}^x}{\partial q_{26}}\dot{q}_{26}}_{Trolley} \quad (2)$$

The left and right strokes were divided into three parts: 0-10% (*entry*), 10-20% (*propulsion*) and 20-30% (*exit*). The dependent variables were the anteroposterior components of the paddle tip velocity and the force applied to the paddle tip. An average value of the velocity and the impulse of the force were calculated for each part. Then the two conditions were compared with a paired *t*-test. Only the results for the right stroke are presented in this abstract.

RESULTS AND DISCUSSION

The lower limbs contribution to the anteroposterior component of the paddle tip velocity was between 0.2 and 0.4 m/s (Figure 2). The main contribution came from the abdomino-thorax segment and the upper-limbs.

Table 1 summarizes the velocity of paddle tip for each part of the stroke. Whoever the kayaker and whatever the part of the stroke, the velocity was higher with the pelvis motion. The gain was 0.15 m/s during the first part and higher than 0.34 m/s after the *entry*. Important differences were noted in a population of elite kayakers. As an example, the contribution reached 0.67 m/s for one kayaker. The asymmetrical movements of the lower limbs comprise an efficient co-ordination to increase the boat velocity.

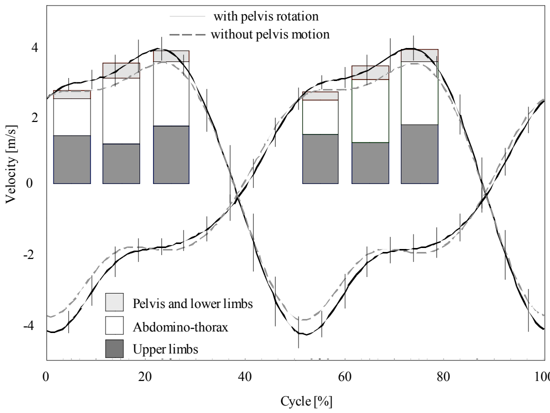

Figure 2: Average (n=26) paddle tip velocity [m/s] with [**C1**] and without [**C2**] pelvis rotation. The stacked columns show the contribution of each body part in generating the velocity.

Table 1: Average velocities (n=26) and standard deviations [m/s] during the right stroke according to the pelvis rotation: with [C1] and without [C2].

	[C1]	[C2]
0-10%	2.72±0.17	2.57±0.15
10-20%	3.25±0.42	2.87±0.37
20-30%	3.57±0.25	3.23±0.27

The difference of paddle tip velocity had consequences to the paddle tip force. Table 2 summarizes the impulse values according to the three parts of the stroke and the two conditions. The total impulse was higher by about 3.5 Ns for the kinematics with lower-limb movements [**C1**]. This value corresponded to a greater impulse of about 6%.

When the pelvis was kept fixed, the force decreased between 0-20%. The most significant difference occurred at the beginning of the stroke. However, the force increased at the end of the stroke.

Table 2: Average (n=26) impulse of the force applied at the right paddle [Ns] with [**C1**] and without [**C2**] pelvis rotation

	[C1]	[C2]	p-value
0-10%	21±8	17±7	<0.0001
10-20%	25±7	23±8	<0.05
20-30%	7±4	8±4	<0.0001
Total	58±7	54±8	0.0001

The relationship between the velocity and the force of the paddle tip is not linear. If we consider then the structure of the vector $\mathbf{q}$: $\mathbf{q}=[\mathbf{q1}\ \mathbf{q2}]^T$, we can split the dynamics (Eq. [1]) to exhibit the same structure:

$$\begin{bmatrix}\mathbf{M}_{1,1} & \mathbf{M}_{1,2}\\ \mathbf{M}_{2,1} & \mathbf{M}_{2,2}\end{bmatrix}\begin{pmatrix}\ddot{\mathbf{q}}\mathbf{1}\\ \ddot{\mathbf{q}}\mathbf{2}\end{pmatrix}+\begin{bmatrix}\mathbf{N}_1\\ \mathbf{N}_2\end{bmatrix}\begin{pmatrix}\dot{\mathbf{q}}\mathbf{1}\\ \dot{\mathbf{q}}\mathbf{2}\end{pmatrix}+\begin{bmatrix}\mathbf{G}_1\\ \mathbf{G}_2\end{bmatrix}=\begin{bmatrix}\hat{\mathbf{o}}\\ \mathbf{0}\end{bmatrix}+\begin{bmatrix}\mathbf{C}_1^T\\ \mathbf{C}_2^T\end{bmatrix}\ddot{\mathbf{e}} \quad (3)$$

where the joint torques do not appear in the lower part:

$$\begin{bmatrix}\mathbf{M}_{2,1} & \mathbf{M}_{2,2}\end{bmatrix}\begin{pmatrix}\ddot{\mathbf{q}}\mathbf{1}\\ \ddot{\mathbf{q}}\mathbf{2}\end{pmatrix}+\mathbf{N}_2\dot{\mathbf{q}}+\mathbf{G}_2=\mathbf{C}_2^T\begin{bmatrix}\lambda_1(\mathbf{q2})\\ \lambda_2(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}})\\ \lambda_3(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}})\end{bmatrix} \quad (4)$$

The paddle tip force depends on paddle kinematics ($\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$) which can be expressed as the kinematics of the trolley plus the kinematics of the paddle with respect to the trolley. A positive net force ($\lambda_1+\lambda_2+\lambda_3$) increases the velocity of the system "*athlete-paddle-trolley*" because of the sliding trolley. Thus, the absolute kinematics of the paddle tip is decreased and then has a consequence for the force.

The lower-limb asymmetrical movements cause the pelvis rotation. This rotation increases the paddle tip amplitude and also its velocity. The force applied to the paddle tips and therefore the performance are increased.

From the simulator, the effect of an increase of pelvis rotation or of new kinematics can be simulated. Moreover the co-ordination between the pelvis rotation and the upper limbs movement can be optimized to increase the performance.

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