SUGGESTION TO ROWERS OBTAINED BY INVERSE DYNAMICS AND FUZZY MODELING

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The aims of this study were to clarify the relationships between rower's partial motions and the rowing performance, i.e. boat speed and efficiency, and to suggest the rower which part of the body he/she should concentrate on. Inverse dynamics found time-series patterns of joint torque power. The power patterns were parameterized to six parameters, amounts and timings of three partial motions, i.e. leg extension, trunk swing and arm pull, during the driving phase of rowing stroke. These parameters are easy for a rower to sense and control one by one. Fuzzy modeling identified the relationship between the parameters and the performance. The obtained linguistic fuzzy rules gave effective suggestion to each rower.

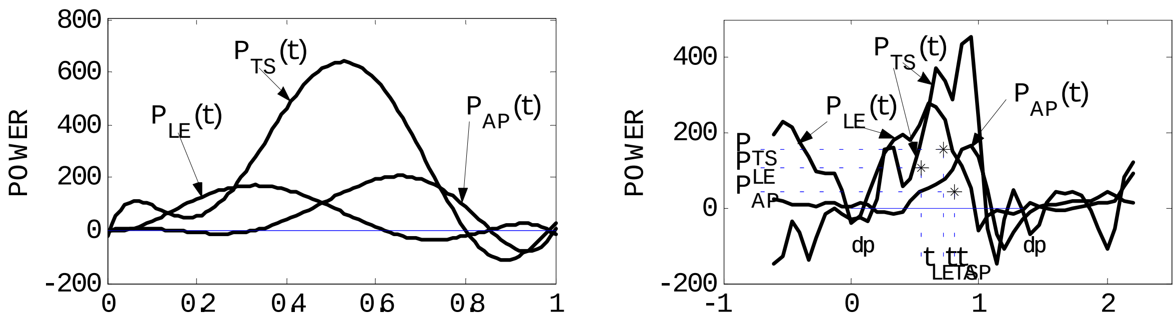
KEY WORDS: rowing, inverse dynamics, joint torque power, fuzzy modeling, identification of nonlinear relationships, suggestions to rowers

INTRODUCTION: Athletes intend to acquire muscle power patterns suitable to the performance. Propulsive power in rowing has been studied (Eldmann 2000; Kleshnev 2000; Smith & Loschner 2000). The propulsive power is the final result of the contributions of the whole body parts. Partial motions, such as leg extension, trunk swing and arm pull, are easier to sense and control for a rower. However, there are two hurdles to give rowers effective suggestions associated with the partial motions. One is that it is hard to measure rower's muscle power directly during on-water rowing. The other is that, by only showing the graphs of partial motions, it is difficult for athletes and coaches to understand which motion is suitable for high performance and which one should be corrected.
Against the first hurdle, this study utilized inverse dynamics (Winter 1990) to calculate power of the partial motions. Against the second one, we utilized fuzzy modeling (Tachibana and Furuhashi 1999). Fuzzy modeling identifies nonlinear relationships with linguistic rules, called fuzzy rules. The input space is divided into subspaces with fuzzy border. Each subspace corresponds to a fuzzy rule. The fuzzy rules are if-then formed, which give us explicit knowledge.
The power patterns of the three partial motions were parameterized. The parameters were the input variables. And the performance indices, i.e. boat speed and efficiency, were the output variables. The obtained fuzzy rules clarified features of each rower and yielded suggestions to rowers for improving their performance.

METHODS: Subjects and measurement: The subjects were seven rowers from a university rowing team. When each of them rowed 100m runs a few times by single scull, forces on oar handles f_{OAR}, oar angles in the horizontal plane θ_{OARy} and the acceleration of the boat were measured. Knee, hip, L4/L5, shoulder, elbow and handle positions were videotaped, digitized and projected to the sagittal plane. The sampling frequency was set at 15 Hz. An electromagnetic speedometer measured average boat speed.
Inverse dynamics: A two-dimensional link segment model with six body segments, i.e. shank, thigh, pelvis, trunk, upper arm and forearm, was constructed. The coordinate system had *x*-axis to the boat direction and *y*-axis to the vertical direction with a reference point on the still water.
Joints forces were calculated from the elbow to the foot: $\mathbf{f}_{i+1} = \mathbf{f}_i + m_i(\mathbf{g} - \ddot{\mathbf{x}}_i)$, where $\mathbf{g} = [0, -g]^T$ was the gravity acceleration, m_i and $\mathbf{x}_i = [x_i, y_i]^T$ were the mass and the position of *i*-th segment,

respectively, double dots denote the second derivative. The hand force was given from the measured variables, $\mathbf{f}_1$ = [$f_{OAR} \sin\theta_{OARy}$, 0]^T. The vertical force on the hip from the seat was estimated by, $f_{SEATy} = (\mathbf{r'}_{HAND} \times \mathbf{f}_1 + \mathbf{r'}_{COG} \times M\mathbf{g}) / x'_{SEAT}$, where $\mathbf{r'}_{HAND}$ and $\mathbf{r'}_{COG}$ were the relative displacement to the foot of the hand and the center of gravity, respectively, *M* was the body mass, x'_{SEAT} was the relative displacement of the seat. The force was added in the equation of pelvis motion. The joint torque T_i was calculated by: $T_{i+1} = T_i + \mathbf{a}_i \times \mathbf{f}_i + \mathbf{b}_i \times (-\mathbf{f}_{i+1}) - I_i \ddot{\theta}_i$, where $\mathbf{a}_i$ and $\mathbf{b}_i$ were the relative displacements of the segment ends to the segment center of mass, I_i and $\ddot{\theta}_i$ were the inertial moment and the angular acceleration, respectively, in the sagittal plane. The joint torque power P_i was calculated by: $P_i = T_i \cdot (\dot{e}_i - \dot{e}_{i-1})$. The efficiency η was (output work) / (output work + internal consumption work), where the output work and the internal consumption work were $\sum_{t=1}^{t1} \{\mathbf{f}_7 \cdot \dot{\mathbf{x}}_7 + (-\mathbf{f}_1) \cdot \dot{\mathbf{x}}_1\}$ and $\sum_{t=1}^{t1} \sum_{i=2}^{7} P_i$, respectively.

Time-series patterns of leg extension power $P_{LE}(t)$, trunk swing power $P_{TS}(t)$, and arm pull power $P_{AP}(t)$ were given by $P_7(t)+P_6(t)$, $P_5(t)+P_4(t)$, and $P_3(t)+P_2(t)$, respectively. Totally 15 runs of the 7 rowers were analyzed. The average patterns of the 15 runs are shown in figure 1 (a). They applied leg extension in the first half, trunk swing in the very beginning and the middle, and arm pull in the second half of the driving phase. The power patterns of each run were parameterized to average value and representative timing during the driving phase as shown with asterisks in figure 1 (b).



(a) Average power during the driving phase (b) Example of parameterization

Figure 1 – Power patterns of partial motions.

Fuzzy modeling: The averages and the timings were the inputs [P_{LE}, P_{TS}, P_{AP}, t_{LE}, t_{TS}, t_{AP}], and the performance indices were the outputs [v, η]. The input-output relationships were nonlinear, with saturations and mutual interactions between variables. A fuzzy model contains plural if-then formed fuzzy rules, for example 'If P_{LE} is *strong*, Then v = 3.76 [m/s]' and 'If P_{LE} is *weak* and P_{AP} is *strong*, Then v = 3.48'. When a pair of inputs is given, each rule has an activation value, according to how *strong* or how *weak* the P_{LE} is in the case of this example. The sum of the consequent singletons of the rules weighted by the activation values is the output of the model. Our fuzzy modeling method found fuzzy rules by dividing the input space into subspaces according to the data distribution in the input-output space. Each of the subspaces corresponds to a fuzzy rule. First, the original input space was divided into two subspaces so as to minimize the model error after the division. Next, one of the two subspaces was divided under the same assessment of division. The division process was repeated until the model evaluation converged. Our method was possible to identify another model to compensate the error of the first model. The same division processes were carried out, using the difference between the original output and the output of the first model as the output of the second model.
To obtain concise models, fuzzy models were identified for the boat speed and for the efficiency, separately.

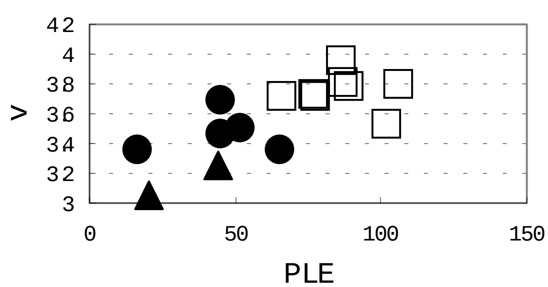
RESULTS AND DISCUSSIONS: The fuzzy rules for the boat speed are shown in the first three rows in table 1. Another model was also identified to compensate the error of the first model.

The fuzzy rules of the second model are shown in the three rows from the bottom. Leg extension power P_{LE} was the most decisive factor for the boat speed. Arm power P_{AP} influenced the boat speed in the case where P_{LE} was small. Trunk power P_{TS} and timing of arm pull t_{AP} affected to some extent. Figure 2 (a) and (b) show the relationships between P_{LE}, P_{AP} and v. Square marks show the data whose activation value of rule A1 was higher than that of A2 or A3. Circles show the data with highest activation in rule A2. Triangles show the data with highest activation in rule A3. Focusing on the data with small P_{LE}, the dependence of v on P_{AP} becomes apparent. Figure 2 (c) and (d) show the relationships between P_{TS}, t_{AP} and the compensation of

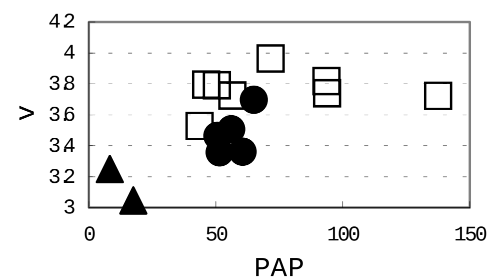
the first model of v. Squares, circles and triangles represent the data with highest activation in rules B1, B2 and B3, respectively. Those graphs show that small P_{TS} decreased the boat speed and that late arm pull with not small P_{TS} increased the boat speed.

Table 1 Fuzzy Rules on the Boat Speed, and Activation Values

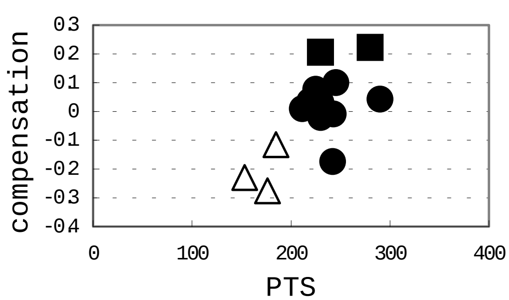
	Antecedent part	*Consequent part*	*Rower* 1	*Rower* 2	wer *3*
A1	If P_{LE} is strong	Then v = 3.76[m/s]	56[%]	93[%]	81[%]
A2	If P_{LE} is weak and P_{AP} is strong	Then v = 3.48	43	7	19
A3	If P_{LE} is weak and P_{AP} is weak	Then v = 3.15	1	0	0
B1	If P_{TS} is strong and t_{AP} is late	Then +0.21 to v	0[%]	36[%]	0[%]
B2	If P_{TS} is strong and t_{AP} is early	Then +0.01 to v	15	60	98
B3	If P_{TS} is weak	Then –0.21 to v	85	4	2



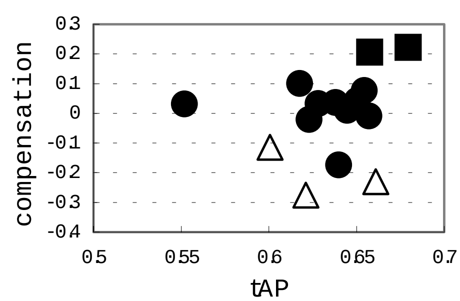
(a) P_{LE} and v



(b) P_{AP} and v



(c) P_{TS} and compensation of v



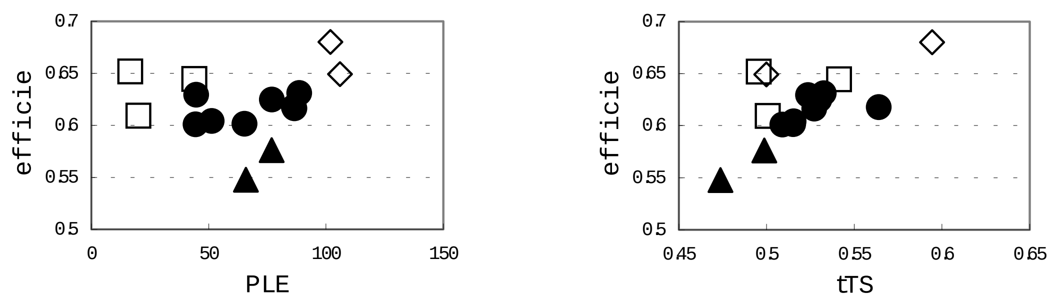
(d) t_{AP} and compensation of v

Figure 2 – Input variables which contributed to the boat speed.

The fuzzy rules for the efficiency η are shown in table 2. P_{LE} affected η mostly. Large P_{LE} meant large output power, so η was large. On the other hand, small P_{LE} meant small internal consumption power, and η was also large in this case. When P_{LE} was medium, η depended on timing of trunk swing t_{TS}. In this case, early trunk swing motion decreased η. Figure 3 (a) shows the relationship between P_{LE} and the efficiency. The data with large P_{LE} and small P_{LE} had high efficiency. Figure 3 (b) shows the relationship between t_{TS} and the efficiency. Focusing on the data with medium leg power makes the dependence of the efficiency on t_{TS} very clear. The activation values of fuzzy rules for 3 rowers are shown in the right three columns of the tables. Looking at rower 1, the activation values of rules A1 and A2 were about half by half. His leg power was not so strong and not so weak, arm power was strong. Those of rules B3 and C3 were both high. That meant his timing of trunk swing was almost good but the trunk power was weak. Rules B2 and C4 were activated slightly. That meant the timings of arm pull and trunk swing were a little too early. Suggestions to the rower 1 were to enlarge trunk and leg power, and to keep the timings of arm and trunk late. The features of rower 2 were high activations of rules A1 and C3. That meant his leg power was strong and the timing of trunk swing was appropriate. Rule B2 had a higher activation than B1, so his timing of arm pull should be corrected to improve the boat speed. Rower 3 had high activations of rules A1 and B2. His power of leg and arm was good. He should correct timing of the arm pull. Rule C4 was activated to some extent. He should also correct timing of the trunk swing.

Table 2 Fuzzy Rules on the Efficiency, and Activation Values

	Antecedent part	*Consequent part*	*Rower* 1	*Rower* 2	Rower 3
C1	**If P_{LE} is strong**	**Then η = 0.67**	**0[%]**	**1[%]**	0[%]
C2	**If P_{LE} is weak**	**Then η = 0.63**	**1**	**0**	0
C3	**If P_{LE} is medium & t_{TS} is late**	**Then η = 0.62**	**87**	**98**	64
C4	**If P_{LE} is medium & t_{TS} is early**	**Then η = 0.56**	**12**	**1**	36



(a) P_{LE} and efficiency (b) t_{TS} and efficiency

Figure 3 – Input variables which contributed to the efficiency.

CONCLUSION: It is hard to measure muscle power directly during on-water rowing. This study used inverse dynamics to depict power patterns of partial motions. Seven university team rowers applied leg power in the first half, trunk power in the very beginning and the middle, arm power in the second half of the driving phase of rowing stroke. Fuzzy modeling identified the relationships between the power of partial motions and the performance. Boat speed depended largely on the leg power. The arm power also contributed to the boat speed. The trunk power and the timing of the arm pull affected to some extent. The efficiency was large when the leg power was strong or weak. When the leg power was medium, early trunk swing decreased the efficiency. Suggestions to each rower were obtained as described in the previous section.

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