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Experimental evaluation of the power balance model of speed skating

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de Koning, Jos. J., Carl Foster, Joanne Lampen, Floor Hettinga, and Maarten F. Bobbert. Experimental evaluation of the power balance model of speed skating. *J Appl Physiol* 98: 227–233, 2005; doi:10.1152/japplphysiol.01095.2003.—Prediction of speed skating performance with a power balance model requires assumptions about the kinetics of energy production, skating efficiency, and skating technique. The purpose of this study was to evaluate these parameters during competitive imitations for the purpose of improving model predictions. Elite speed skaters ($n = 8$) performed races and submaximal efficiency tests. External power output (P_o) was calculated from movement analysis and aerodynamic models and ice friction measurements. Aerobic kinetics was calculated from breath-by-breath oxygen uptake ($\dot{V}O_2$). Aerobic power (P_{aer}) was calculated from measured skating efficiency. Anaerobic power (P_{an}) kinetics was determined by subtracting P_{aer} from P_o. We found gross skating efficiency to be 15.8% (1.8%). In the 1,500-m event, the kinetics of P_{an} was characterized by a first-order system as $P_{an} = 88 + 556e^{-0.0494t}$ (in W, where t is time). The rate constant for the increase in P_{aer} was -0.153 s^{-1}, the time delay was 8.7 s, and the peak P_{aer} was 234 W; P_{aer} was equal to $234[1 - e^{-0.153(t - 8.7)}]$ (in W). Skating position changed with preextension knee angle increasing and trunk angle decreasing throughout the event. We concluded the pattern of P_{aer} to be quite similar to that reported during other competitive imitations, with the exception that the increase in P_{aer} was more rapid. The pattern of P_{an} does not appear to fit an "all-out" pattern, with near zero values during the last portion of the event, as assumed in our previous model (De Koning JJ, de Groot G, and van Ingen Schenau GJ. *J Biomech* 25: 573–580, 1992). Skating position changed in ways different from those assumed in our previous model. In addition to allowing improved predictions, the results demonstrate the importance of observations in unique subjects to the process of model construction.

sport performance; modeling; muscular power output; aerobic power; anaerobic power

DURING THE PAST TWO DECADES, our understanding of human locomotor behavior has evolved substantially, from phenomenological descriptive studies of individuals who ambulate remarkably well (e.g., athletes), to correlative studies of the range of ambulatory capabilities across the population, to models that allow quantitative prediction of locomotor behavior (8, 11, 13, 14, 23, 27, 28, 36, 38). Among these is the power balance model developed in our laboratory (11, 36), which has been reasonably successful in predicting performance in cyclic events (e.g., running, cycling, and speed skating) (7, 11, 12, 39). The power balance model, which relates power production and power dissipation, can be written as

$$P_o = P_f + dE_{mcb}/dt \qquad (1)$$

where P_o is the average total power output of the skater, P_f is the average power loss to air and ice friction, and dE_{mcb}/dt is the average change of the kinetic, rotational, and potential energy of the body. The rate of change of mechanical energy of the body during speed skating is determined by the rate of change of kinetic energy of the mass center

$$dE_{mcb}/dt = d(1/2 mv^2)/dt = mv(dv/dt) \qquad (2)$$

where m is body mass and v is the average speed. The rate of change of kinetic energy can thus be expressed as

$$P_o - P_f = d(1/2 mv^2)/dt \qquad (3)$$

The value of any model is critically dependent on the quality and validity of the components of the model. To simulate skating performance, it is necessary to have expressions for P_o and P_f. Aerobic power (P_{aer}) production can be estimated from measures of oxygen uptake ($\dot{V}O_2$), which includes both the maximal $\dot{V}O_2$ ($\dot{V}O_{2\,max}$) and the kinetics of $\dot{V}O_2$, which have been modeled as

$$\dot{V}O_2 = \dot{V}O_{2max}[1 - e^{-\lambda(t - t_d)}] \qquad (4)$$

where λ is a rate constant and t_d a time delay (1), and from measures of efficiency. The present expression of these parameters in the model (8, 12) is based on $\dot{V}O_{2\,max}$, $\dot{V}O_2$ kinetics, and gross efficiency measures from cycling. $\dot{V}O_{2\,max}$ during skating is substantially less than during cycling (10, 21). Recent evidence also suggests that gross efficiency during skating is also less than during cycling (10, 21). $\dot{V}O_2$ kinetics during skating has not been measured.

The anaerobic contribution to P_o can be estimated from measurements of total and aerobic energy output:

$$P_{an} = P_o - P_{aer} \qquad (5)$$

and the resulting anaerobic power (P_{an}) output can be modeled by a first-order system (8) as

$$P_{an} = P_{an}\text{-con} + P_{an}\text{-max} \times e^{-\gamma t} \qquad (6)$$

where P_{an}-con is the mechanical P_{an} at the end of the race, P_{an}-max is the maximal mechanical P_{an} at $t = 0$ minus the value of P_{an}-con, and γ is a rate constant. The present model uses an expression for how anaerobic energy is distributed based on laboratory cycling tests where subjects have been constrained to adopt an "all-out" approach to performance. More recent data (15) from studies in which athletes were allowed to adopt a freely chosen pattern of energy distribution

have suggested that the pattern of distributing P_{an} may be quite different. Moreover, the magnitude of P_{an} is apparently highly variable. Just as P_{aer} is quite different from cycling to skating, it stands to reason that values of P_{an} chosen from the cycling literature may not represent P_{an} during skating.

Just as there are concerns within the model related to power production, there are also some concerns regarding power dissipation:

$$P_f = P_{air} + P_{ice} \quad (7)$$

where P_{air} is the power to overcome the air friction force (F_{air}) and P_{ice} is the power to overcome the ice friction force (F_{ice}). The most important of the dissipating forces is air friction:

$$F_{air} = 1/2\rho v^2 A_p C_d \quad (8)$$

where ρ is the density of air (kg/m^3), v is the velocity of the air with respect to the body (m/s), A_p is the frontal area projected to the air (m^2), and dimensionless unit C_d is drag related to streamlining. Wind tunnel experiments have shown that F_{air} depends largely on anthropometric variables and the skater's body position, particularly hip and knee angles during the gliding phase of the stroke:

$$F_{air} = 0.0205 lm^{1/3}\rho_0 e^{-0.000125h} F(\theta_1)G(\theta_o)H(v)v^2 = kv^2 \quad (9)$$

where l is the body height (m), m is the body mass (kg), ρ_0 is air density at sea level (kg/m^3), h is the altitude above sea level (in m), $F(\theta_1)$ and $G(\theta_o)$ are expressions that account for trunk position (θ_1) and knee angle (θ_o), respectively, $H(v)$ is the influence of the velocity on the drag coefficient, and k is the resulting air friction coefficient (kg/m) (35). The present model parameters are based on filming studies that have established reasonable trunk position and knee angles for elite speed skaters (12, 37). In the present model, these angles are assumed to remain constant throughout the duration of a competition. However, even casual observations of competitive skaters will demonstrate that trunk position and knee angle change during a competition.

The present power balance model can be used to predict final time in speed skating competitions relatively well (8, 12, 38). However, the ability of the power balance model to predict the momentary velocity profile leaves room for improvement. These deficiencies are reasonably attributable to the untested assumptions of the kinetics of $\dot{V}O_2$, of gross skating efficiency, of the magnitude and distribution of P_{an}, and of changes in trunk position and knee angle. This is important if one wants to have the model applicable to individual athletes rather than solely for the prediction of group behavior. One critical step in the process of modeling is revision on the bases of better observational or experimental data. For example, both climatic and planetary collision models have been extensively revised on the basis of improved observations (29, 40). Accordingly, it was the purpose of this study to evaluate these parameters in elite-level speed skaters during imitated competition with the intent of testing the power balance model. Specifically, we proposed to evaluate parameter values in a group of elite speed skaters, to compare these values with those presently used in the model, and to compare the ability of the model to predict momentary velocity and final time with both old and new parameter values.

METHODS

Subjects. The subjects for this study were elite ice speed skaters (6 men, 2 women). Seven were members of the Dutch Junior National Speed Skating Team; the other was a high-level neo-senior with a performance level just below national level. They were studied in mid-November, just before the first competitions of the year. By the end of the skating year, two of the skaters became mens and ladies Junior World Champions, and members of the entire group held 8 of the 11 Junior World Records recognized by the International Skating Union. All subjects provided informed consent before participation. The university human subjects committee approved the protocol. Descriptive characteristics of the subjects are provided in Table 1.

Protocol. The subjects were studied during skating on an indoor 400-m oval (Groningen, The Netherlands) during submaximal- and competitive-level performances on 2 days. On the subsequent weekend, each subject skated a 1,500-m race during a sanctioned competition. On *day 1*, every subject performed a submaximal effort of six laps (~4 min), at a pace intended to be slow enough to be sustainable for 30–60 min. This effort was designed to allow for measurement of steady-state $\dot{V}O_2$ to calculate skating efficiency. After an ~5-min rest, each subject performed a 1,500-m time trial at competitive effort. The 1,500 m is a middle-distance event, which is widely accepted as representative of speed skating events, and is regularly performed by both sprint and long-distance competitors. The only instruction to the subjects was to finish the trial in the shortest possible time, as they would in competition. During the trial, the Junior National Team coach provided lap times and coaching advice during the event, just as in a normal competition. Velocity was measured by fixed-position time traps placed at 100-m intervals around the track. Trunk angle and preextension knee angle were measured twice per lap (while the skaters were on the straight section of the track) from sVHS video cameras placed in the center of the track. We measured $\dot{V}O_2$ breath-by-breath using open-circuit spirometry with a portable metabolic system (Cosmed K4b^2, Rome, Italy). Lactate was measured spectrophotometrically (Dr. Lange, Dusseldorf, Germany) in capillary blood samples obtained ~1 min after the submaximal effort and ~3 min after the competitive effort. Mechanical P_o for each 200-m segment of both submaximal and maximal skating was calculated from velocity, air density, and skating position (according to *Eqs. 3* and *9*). We measured ice friction using an instrumented skate (9). Gross efficiency was calculated from the respiratory gas-exchange measurements, the energy equivalent of oxygen (20), and from the mechanical P_o during submaximal skating. Gross skating efficiency was defined as the mechanical P_o divided by the metabolic power generated by the aerobic energy system (11). The aerobic contribution to performance during the 1,500-m skate was calculated based on $\dot{V}O_2$ during the 1,500-m event and gross efficiency from submaximal skating (15, 30, 31).

On *day 2*, each athlete again performed a six-lap submaximal effort to allow determination of gross efficiency. After an ~5-min rest, each athlete performed a second competitive-level effort, this time with a distance reflecting the event specialization of the athlete (500 m: $n = 2$, 1,000 m: $n = 2$, 3,000 m: $n = 2$, 5,000 m: $n = 2$). As in the 1,500-m skate, every effort was made to imitate a competitive situation by

Table 1. *Descriptive characteristics of the subjects*

Parameter	Men ($n = 6$)	Women ($n = 2$)
Age, yr	18.2 ± 1.0	18.5 ± 0.7
Height, cm	186.2 ± 3.5	170.0 ± 4.2
Body mass, kg	82.2 ± 9.6	64.0 ± 5.6
$\dot{V}O_{2peak}$,* 1/min	4.75 ± 0.4	3.23 ± 0.3
$\dot{V}O_{2peak}$, ml·min^{-1}·kg^{-1}	57.9 ± 4.2	50.5 ± 0.4

Values are means $\pm$ SD. $\dot{V}O_{2peak}$, peak oxygen uptake. *Measured during 1,500-m skating. $\dot{V}O_{2peak}$ during cycle ergometry is typically 110% of that observed during skating.

having the coach provide lap times and technical advice during the trial. Measurements of skating velocity, technique, and $\dot{V}O_2$ were the same as during the 1,500-m skate.

After data reduction, we calculated the mean velocity, skating position, and P_o (total, aerobic, anaerobic) for appropriate segments of each imitated competition. For the 500-m and 1,500-m skates, we did this for the first 100 m and for every successive 200 m. For the 1,000-, 3,000-, and 5,000-m skates, we did this for every 200 m. This allowed matching of changes in velocity with changes in P_o and skating technique during common segments. The rate constant of $\dot{V}O_2$ was calculated by modeling temporal changes in $\dot{V}O_2$ as described by Barstow et al. (1). Phase 1 was determined on the basis of the respiratory exchange ratio. Phase 2 was fitted by using a monoexponential model, which we have found fits the data well during very high-intensity exercise of this duration (0.6–7 min). The P_{an} production was modeled with the monoexponential function given in *Eq. 6*.

The previously described power balance model (11, 38) was used to calculate velocity profiles of 1,500-m races, as was done in previous studies, based on data from cycling and the assumption of constant skating position. Performance times and 400-m split times from the official 1,500-m event performed during the subsequent weekend were used to compare the calculated velocity from the power balance model with actual speed skating performance and to compare the imitated competition with actual competition.

RESULTS

The mean ($\pm$SD) times for completion of the competitive event were as follows: 500 m = 38.38 $\pm$ 0.73 s, 1,000 m = 76.41 $\pm$ 0.45 s, 1,500 m = 121.63 $\pm$ 6.51 s, 3,000 m = 252.26 $\pm$ 10.25 s, and 5,000 m = 426.09 $\pm$ 26.02 s. Compared with the 1,500-m skate in the official race, the imitated 1,500-m competition was performed at a relative velocity of 95.2 $\pm$ 1.3% and was well correlated with the real performances ($r = 0.94$) ($P < 0.05$). The mean ($\pm$SD) blood lactate concentration measured 1 min after the submaximal skating effort was 3.8 $\pm$ 0.8 mmol/l. This is well below the blood lactate concentration usually observed at the maximal lactate steady state during speed skating ($\sim$6.5 mmol/l) (3, 16, 18). The mean ($\pm$SD) blood lactate concentration measured 3 min after the 1,500-m competitive imitation was 15.4 $\pm$ 1.9 mmol/l, which is within normal postcompetition blood lactate concentrations following speed skating competition (16, 18). Similarly, the range of blood lactate concentrations after the other competitive imitations (9.4–17.8 mmol/l) was similar to previously reported values (16, 18). The velocity, magnitude, and pattern of the $\dot{V}O_2$ response as well as of blood lactate concentration indicate that the submaximal skating effort

was truly submaximal (and thus valid for gross efficiency estimation) and that the competitive imitations were reasonable approximations of competitive effort. The mean ($\pm$SD) gross efficiency measurements during the two submaximal trails were 15.4 $\pm$ 1.5 and 16.3 $\pm$ 1.9%, resulting in a mean gross efficiency of 15.8 $\pm$ 1.8%. This is similar to other values observed in speed skaters (21).

Below, we will focus on results of the 1,500-m event, which was performed by all of the subjects. Some general comparisons will also be made on the basis of the partial samples (subgroups of subjects) that performed each of the other events. The pattern of velocity during the competitive imitations is presented in Fig. 1. The patterns of velocity were typical of those ordinarily seen during speed skating competitions, i.e., a rapid acceleration followed by a progressive deceleration during the 1,000-m and 1,500-m races and a more or less constant velocity in the 3,000-m and 5,000-m races. The mean ($\pm$SD) velocity measured during each segment of the 1,500-m skate is presented in Table 2.

The mean pattern of $\dot{V}O_2$ during the competitive imitations is presented in Fig. 2. In the 1,500-m event, the rate constant for the increase in $\dot{V}O_2$ was 0.153 s^{-1} and the time delay was 8.71 s. This was more rapid than used in our previous simulations (8, 12, 39), which were based on laboratory data of 4-km time trials on the cycle ergometer and data from literature, rather than competitive imitations during skating.

The patterns of calculated total P_o, P_{aer}, and P_{an} are presented in Fig. 3. The mean ($\pm$SD) values for total P_o, P_{aer}, and P_{an} in the 1,500-m competitive imitation are presented in Table 2. In contrast to the parameter values used in the model, the pattern of anaerobic energy use does not appear to fit an "all-out" pattern, with near zero values (P_{an}-con = 0) during the last 25% of the event. The same was true for the other events. In the 1,500-m event, there was even a slight increase in total P_o during the terminal portion of the event, attributable to an increase in P_{an} (Table 2).

The patterns of changes in the preextension knee angle and trunk angle in relation to the distance completed are presented in Fig. 4. Unlike the assumption underlying our previous simulations, neither the knee nor the trunk angles were constant throughout the duration of the competitive imitation. The mean ($\pm$SD) preextension knee angle and trunk angles for the 1,500-m competitive imitation are presented in Table 2.

The relationship between changes in skating position, calculated as a combined parameter representing the air friction
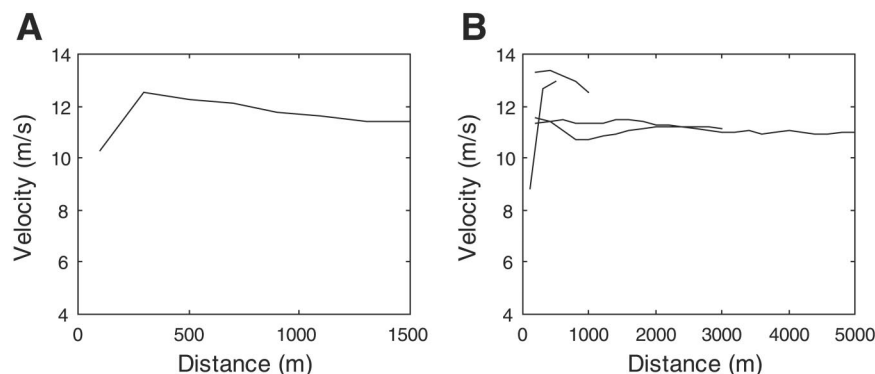
A

B

Fig. 1. Velocity in the 1,500-m (*A*) and the 500-m, 1,000-m, 3,000-m and 5,000-m (*B*) competitive imitations.

Table 2. *Responses during segments of the 1500-m competitive imitation*

Distance, m	Velocity, m/s	$\dot{V}O_2$, l/min	P_{total}, W	P_{aer}, W	P_{an}, W	Knee Angle, degrees	Trunk Angle, degrees
100	10.32±0.29	1.44±0.49	553.8±115.9	100.8±26.1	453.0±117.3	98.0±9.0	25.8±5.9
300	12.51±0.54	3.33±0.42	487.7±113.9	193.6±30.1	294.1±87.8	99.5±10.0	22.2±4.2
500	12.28±0.76	4.16±0.65	357.3±86.4	227.4±38.6	129.8±45.1	106.3±8.5	19.7±3.7
700	12.12±0.84	4.24±0.73	343.8±80.4	232.8±39.6	111.0±50.8	106.9±12.7	21.6±4.5
900	11.76±0.89	4.22±0.77	324.6±63.4	230.6±39.1	94.0±43.4	107.7±10.0	20.0±4.8
1,100	11.64±0.86	4.17±0.79	326.4±75.6	228.0±32.8	98.4±44.8	110.1±12.8	20.8±4.4
1,300	11.40±0.87	4.14±0.79	314.7±61.5	226.2±36.0	88.5±36.9	110.3±9.3	21.7±4.4
1,500	11.42±0.79	4.09±0.78	333.3±84.8	222.4±39.8	110.9±66.4	108.6±9.9	23.0±5.1

Values are means ± SD. $\dot{V}O_2$, oxygen uptake; P_{total}, total power output; P_{aer}, aerobic power output; P_{an}, anaerobic power output.

coefficient (k) in *Eq. 9*, and changes in velocity during the 1,500-m event are presented in Fig. 5. On the basis of the magnitude of R^2 from this relationship, ~42% of the variation in velocity can be accounted for by variations changes in skating position.

Velocity profiles calculated with the model and the velocity obtained from the official 1,500-m race are presented in Fig. 6 and Table 3. It can be seen that the velocity calculated with the power balance model based on data from the skating imitation presented in this study fits reality better that the velocity calculated based on cycling data.

DISCUSSION

The power balance model of skating performance has been demonstrated to be comparatively successful in predicting average skating performance (8, 11, 12, 38). The main result of the present investigation is that three important parameter values in the present version of the power balance model, namely, the constancy of skating position, the pattern of anaerobic energy use, and the rate constant of $\dot{V}O_2$, are not consistent with measurements of these parameters during imitated competition, suggesting that the model should be modified.

Although changes in skating position throughout the course of a competition are apparent to even the most casual observer of speed skaters, systematic measurements of skating position during competition have never previously been reported. The changes are in the direction predicted based on evidence for restriction of muscle blood flow during speed skating (18). As the athletes fatigue, they seem to be less able to tolerate the deeply crouched position that is most favorable both for reducing wind resistance and for optimizing the push off. These data are consistent with other

data demonstrating a reduction of positional sense and motor control in fatigued muscle (24). They are also consistent with reductions in force-generating capacity with fatigue (33). Progressive increases in the preextension knee angle would require a smaller muscular force at the beginning of the push-off phase of the stroke. The failure to observe a progressive increase in the preextension knee angle in the present data suggests that the skaters reach a dynamic equilibrium between the need to achieve an optimal skating position and the effects of fatigue on their ability to maintain this position. Thus the assumption in the present version of the power balance model of a constant skating position throughout the course of the event is not consistent with the behavior of the skaters. The combined changes in knee and trunk angle during the race result in an increase in air friction coefficient k (Fig. 5). Despite our efforts to create a competitive environment, it must be acknowledged that the present data represent less than all-out competition. We suspect that, under full competitive conditions, the deterioration of skating position may be more extreme. We have previously demonstrated that the magnitude of desaturation in the quadriceps during skating is related to the skaters' positions, particularly their preextension knee angle (18). We have also demonstrated during static exercise that the magnitude of desaturation is related to the effective force generated by the muscle. In this context, increases in preextension knee angle with fatigue can be seen as adaptive responses designed to allow the athlete to maintain P_o throughout the race, although the skaters do not consciously change their skating position. We believe that the changes in skating position are an unconscious response to fatigue that act to minimize the already large decrease in P_o.

Fig. 2. Oxygen uptake ($\dot{V}O_2$) in the 1,500-m (*A*) and the 500-m, 1,000-m, 3,000-m, and 5,000-m (*B*) competitive imitations.
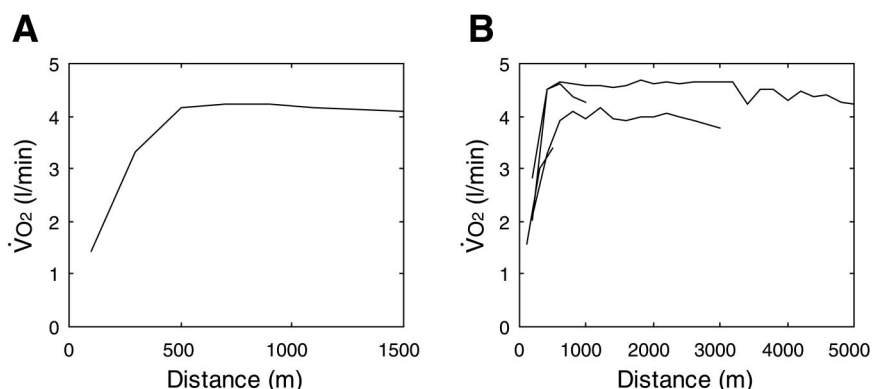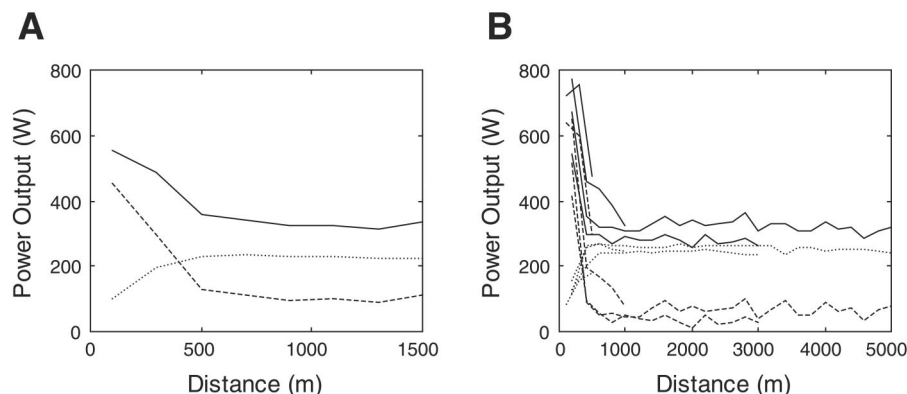
Fig. 3. Total power output (solid lines), aerobic power output (dotted lines), and anaerobic power output (dashed lines) during the 1,500-m (*A*) and the 500-m, 1,000-m, 3,000-m, and 5,000-m (*B*) competitive imitations.

Although peak $\dot{V}_{O_2}$ responses have previously been reported during ice speed skating (12, 21, 37), to our knowledge these are the first data of serial $\dot{V}_{O_2}$ responses during competitive-intensity speed skating. The pattern is quite similar to that reported during imitated competition on the bicycle (7, 17, 19), with running (5), and with kayak performance (4), with the exception that the increase in $\dot{V}_{O_2}$ at the beginning of the trial is more rapid. The mechanical power equivalent generated by the aerobic energy system during imitated skating competition can be described by

$$P_{aer} = 234[1 - e^{-0.153(t - 8.7)}] \ (W) \qquad (10)$$

The rate constant together with the time delay resulted in a mean response time of 15.2 s, which means that 63% of the maximal aerobic response is reached in 15.2 s from the start. Such fast adaptations have not been reported in the literature. The rapidity of the increase in P_{aer} at the beginning of the competitive imitation argues that aerobic kinetics in high-level athletes under competitive circumstances may be more rapid than generally believed on the basis of data from square-wave rest to exercise transitions (2). Whether this is related to the unique gas-exchange characteristics of elite athletes or to the very high initial P_o is unclear. It may also be related to unique characteristics of skating, where limitations of muscle blood flow may create a ceiling of $\dot{V}_{O_2}$ long before the central circulatory adaptation to exercise is complete. This might explain the relatively low $\dot{V}_{O_2 \ max}$ as measured during skating by these world-class athletes (range between 3.23 and 4.75 l/min) and elite speed skaters in general (6) as well as the difference in $\dot{V}_{O_2}$ between cycling and speed skating (10, 22).

The pattern of P_o during the events is consistent with a monitoring process whereby the subjects use their anaerobic energetic reserves to allow for a rapid acceleration and to prevent a considerable slowdown at the end of the event. Only in the longer events does anaerobic energy expenditure go to very low values (<50 W), which seems reasonable. According to *Eq. 6*, the mechanical P_{an} production during the imitated 1,500-m event can be described by

$$P_{an} = 88 + 556e^{-0.0494t} \ (W) \qquad (11)$$

This means that, during the 1,500-m event, the skaters used 21.9 kJ of anaerobic energy to accelerate and overcome ice and air resistance. This value is comparable to the amount of anaerobic energy released during 1,500-m cycling time trials (15) and 800-m running (32). Unlike the predictions of an "all-out" starting strategy that might have been expected during the 1,000-m and 1,500-m events, the athletes seemed to retain an appreciable anaerobic energetic reserve that they used during the closing stages of the event to prevent further deceleration. Whether these data support a neurologically mediated governor as suggested by St. Clair Gibson et al. (33) or whether they represent a feedback process dependent on monitoring metabolite accumulation, phosphagen depletion, or other perceptual cues (34) is unclear at this time. Data from our laboratory (15) suggest that this process is learned fairly quickly. Empirical data from track cycling (41) suggest that successful athletes are skilled at this monitoring process and at preventing a large slow down late in the event by regulation of their early pace (e.g., P_o). This leads one to suspect that the choice of whether to react to, or to ignore, information about
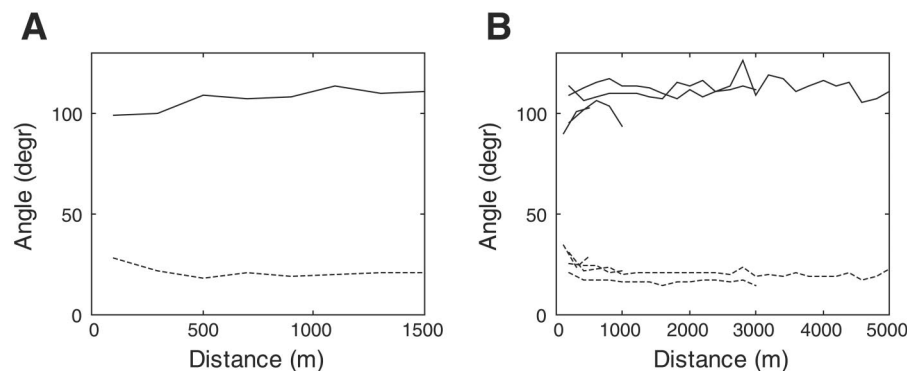

Fig. 4. Preextension knee angle (solid lines) and trunk angle (dashed lines) during the 1,500-m (*A*) and the 500-m, 1,000-m, 3,000-m, and 5,000-m (*B*) competitive imitations. degr, Degrees.
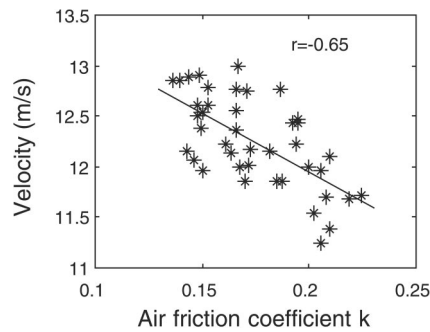
Fig. 5. Relationship between changes in the air friction coefficient (*k*) calculated from preextension knee angle and trunk angle and changes in velocity during the 1,500-m event.

Table 3. *Split and final times of model calculations and differences with the real race*

Distance, m	Previous Model, s	Difference, %	Modified Model, s	Difference, %	Race, s
300	25.78	0.8	27.01	−3.9	26.00
700	54.58	2.4	56.62	−1.2	55.94
1,100	87.56	−0.1	88.42	−1.1	87.46
1,500	124.97	−3.8	121.63	−1.0	120.40

the continuing availability of anaerobic energetic reserves is an active decision process by the athlete.

One can argue that the continuous anaerobic contribution throughout the 1,500-m event (88 W in the presented model) is caused by an underestimation of gross efficiency. According to *Eq. 5*, an underestimation of the gross efficiency and thus an underestimation of the aerobic contribution will result in an overestimation of the P_{an}. In this study, we found an average gross efficiency during submaximal skating of 15.8%. This value is similar to values of speed skating reported in literature and in line with the biomechanical features of the speed skating movement (12, 21). It is possible to calculate what the efficiency would have been in the case that this anaerobic contribution was, in fact, aerobic in nature. In that case, the gross efficiency would have a value of 21.7%, which is higher than the gross efficiency measured in speed skaters during cycling (10) and a high value for cyclists (26). In such a case, the resulting anaerobic energy production during the 1,500-m event would have the unrealistically low value of 11.3 kJ. This seems unlikely because speed skaters consistently demonstrate relatively large anaerobic capacities with a number of testing scenarios (15, 25).

A comparison of the predicted vs. actual performances in the speed skating competition, based on our previously published model (8, 12, 38) and on the model modified for the different assumptions about skating position, $\dot{V}O_2$ kinetics, and anaerobic energy use, is presented in Fig. 6 and Table 3. It is obvious that the model with the modified parameters performs better in predicting the velocity profile during the real competition. The

higher peak velocity and larger slowdown of the model with the old parameters relative to the new one can be explained by the more all-out kinetics of the anaerobic energy system used in the previous model parameters. The split and final times presented in Table 3 show that the prediction of the modified model is closest to the times skated during the official 1,500-m race.

The results of this study demonstrate *1*) the importance of testing experimental models under the most representative conditions available and *2*) the possibility of understanding the interaction of factors contributing to athletic performance. Previous data have largely been collected in laboratory situations and often with exercise strategies that have been imposed by the investigators with little regard as to how athletes actually behave in competition. Only within the last few years has the value of competitive imitations, in which the performance criterion is to finish the event in minimal time, become recognized. Furthermore, although the pattern of energy expenditure during cycling performance is generally similar to that observed during skating, the results of this study relative to $\dot{V}O_2$ kinetics suggest that investigators must pay careful attention to differences in both the mode of exercise and the quality of subjects. In this study, we were most fortunate to be able to study truly world-class athletes under comparatively realistic competitive imitations. The differences in the pattern of response (particularly $\dot{V}O_2$ kinetics) between the present subjects and those of the well-trained but subelite athletes in recent reports from our laboratory (12, 15) clearly demonstrate the importance of this point. At the same time, the only realistic possibility of understanding the behavior of top athletes during high-level competition rests in the use of models such as the power balance model coupled with simple and nonintrusive measurements.

In the larger sense, the results of the present study demonstrate the value of the modeling approach to understand human locomotor behavior. Although the present results apply to elite speed skaters, the results demonstrate that the locomotor behavior of any group of humans can be understood within the context of a power balance model. Accordingly, factors that might improve or hinder performance can be evaluated efficiently with modeling rather than with empirical methods.
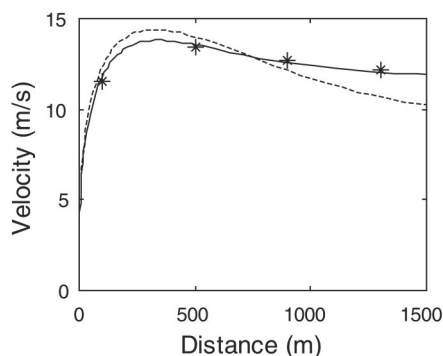

Fig. 6. Velocity profiles calculated with the previous (dashed line) and modified model parameters (solid line) and the velocity obtained from the real 1,500-m race (*).

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