**Section:** Original Investigation

**Article Title:** Historical Improvement in Speed Skating Economy

**Authors:** Dionne A. Noordhof[1], Elmy van Tok[1], Florentine S. J. G. M. Joosten[1], Florentina J. Hettinga[3], Marco J. M. Hoozemans[1], Carl Foster[2,1], and Jos J. de Koning[1,2]

**Affiliations:** [1]MOVE Research Institute Amsterdam, Faculty of Behavioural and Movement Sciences, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, The Netherland. [2]Department of Exercise and Sport Science, University of Wisconsin-La Crosse, WI, USA [3]School of Biological Sciences, Centre of Sport and Exercise Science, University of Essex, UK.

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# Historical Improvement in Speed Skating Economy

Original investigation

Dionne A. Noordhof[1], Elmy van Tok[1], Florentine S. J. G. M. Joosten[1], Florentina J. Hettinga[3], Marco J. M. Hoozemans[1], Carl Foster[2,1], and Jos J. de Koning[1,2]

[1]MOVE Research Institute Amsterdam, Faculty of Behavioural and Movement Sciences, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, The Netherlands
[2]Department of Exercise and Sport Science, University of Wisconsin-La Crosse, WI, USA
[3]School of Biological Sciences, Centre of Sport and Exercise Science, University of Essex, UK

Correspondence: Dionne A. Noordhof
Move Research Institute Amsterdam
Faculty of Behavioural and Movement Sciences
Department of Human Movement Sciences
Vrije Universiteit Amsterdam
Van der Boechorststraat 9
1081 BT Amsterdam
The Netherlands
Tel: +31/20/5982000
Fax: +31/20/5988529
d.a.noordhof@vu.nl

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## Abstract

Half the improvement in 1500-m speed-skating world records can be explained by technological innovations and the other half by athletic improvement. It is hypothesized that improved skating economy is accountable for much of the athletic improvement. ***Purpose:*** To determine skating economy in contemporary athletes and to evaluate the change in economy over the years. ***Methods:*** Contemporary skaters of the Dutch national junior team (n=8) skated 3 bouts of 6 laps at submaximal velocity, from which skating economy was calculated (in mL $O_2 \cdot kg^{-1} \cdot km^{-1}$). A literature search provided historic data of skating velocity and submaximal $\dot{V}O_2$ (in mL$\cdot kg^{-1} \cdot min^{-1}$), from which skating economy was determined. The association between year and skating economy was determined using linear regression analysis. Correcting the change in economy for technological innovations resulted in an estimate of the association between year and economy due to athletic improvement. ***Results:*** An average (±SD) skating economy of 73.4±6.4 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ was found in contemporary athletes. Skating economy improved significantly over the historical timeframe (-0.57 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ per year, 95% confidence interval [-0.84, -0.31]). In the final regression model for the klapskate era, with altitude as confounder, skating economy improved with a non-significant -0.58 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ each year ([-1.19, 0.035]). ***Conclusions:*** Skating economy was 73.4±6.4 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ in contemporary athletes and improved over the past ~50 years. The association between year and skating economy due to athletic improvement, for the klapskate era, approached significance, suggesting a possible improvement in economy over these years.

**Keywords**: Performance, Efficiency, Aerobic Capacity, Cyclic Sports

## Introduction

Speed skating performances have improved considerably over the last decades. For example, during the 1956 Olympic Winter Games the Russian skaters Yevgeniy Grishin and Yuriy Michaylov skated a new world-record time on the 1500-m, of 2:08.6. Currently, the 1500-m world record is 1:41.04, skated in 2009 by the American Shani Davis. De Koning[1] showed, on the basis of model calculations, that about half of the performance improvement in 1500-m world records was due to technological innovations (e.g. indoor ovals, klapskates, etc.) and that the remaining part could be ascribed to athletic improvement. Athletic performance can be described by a variety of physiological factors, as presented in the model of Joyner et al.[2] The four main physiological factors that are required to permit exceptional performances are: 1) maximal oxygen uptake ($\dot{V}O_{2max}$), 2) oxygen uptake ($\dot{V}O_2$) at the ventilatory threshold, 3) anaerobic capacity, and 4) the ability to convert aerobic and anaerobic energetic resources (1-3) to forward propulsion, i.e. gross efficiency.[2,3] Improving one or more of these physiological factors will increase the mechanical power output (or speed) produced by the athlete. Based on a literature search, de Koning[1] concluded that anaerobic capacity (mentioned as muscle power output by de Koning[1]) and $\dot{V}O_{2max}$ have remained relatively constant in elite speed skaters over the past 50 years. Therefore, the most likely cause of the athletic improvement from 1956 till 2009 seems to be an improvement in speed-skating efficiency.[1]

Gross efficiency, the most commonly used measure of whole-body efficiency, is defined as the ratio between mechanical power output and metabolic power input, expressed as a percentage.[4,5] Consequently, the mechanical power output delivered by the athlete needs to be known to determine skating efficiency. However, mechanical power output cannot be measured directly during speed skating, as can be done during cycling.[6,7] Only by calculating the power losses due to ice and air friction during skating at a constant velocity, can an indirect estimate of mechanical power output be obtained.[8,9] Because of the difficulties with directly measuring skating efficiency, an alternative measure, skating economy, defined as the submaximal $\dot{V}O_2$ expressed in $mL \cdot kg^{-1} \cdot km^{-1}$,[10] can be used. This measure has become well-accepted in studies of running performance.[10]

As an improvement in speed skating efficiency/economy seems to be the most likely cause of the athletic improvement from 1956 to now, the first goal of this study was to determine skating economy in contemporary athletes. In addition, the second goal of this study was to evaluate the change in speed skating economy over the years. Correcting the change in skating economy over the years for technological innovations and environmental conditions results in an estimate of the association between year and economy due to athletic improvement. It is hypothesized that speed skating economy has improved over the last decades and that, even after correcting for technological innovations and environmental conditions, this improvement is present.

## Methods

### Speed skating economy of contemporary athletes

*Subjects*

Skaters of the Dutch national junior team (4 males, 4 females; age men 18 ± 1 yr (mean ± standard deviation, SD), women 17 ± 1 yr; height men 186 ± 6 cm, women 172 ± 3 cm; body mass men 78.2 ± 4.8 kg, women 62.6 ± 4.2 kg) participated in this study. In the competitive season in which the measurements were performed, these skaters of the Dutch national junior team won three medals at the World Junior Championships Distances and one medal at the World Junior Allround Championship. Before the start of the test, subjects and their parents/guardians were instructed about the purpose and study protocol, after which subjects and their parents/guardians, in subjects < 18 yr, provided written informed consent.

In addition, subjects completed a health history form. The local ethics committee approved the study protocol, which followed the principles outlined in the Declaration of Helsinki.

*Experimental design and data acquisition*

The speed-skating test consisted of three exercise bouts of six laps (~2400 m) at a submaximal intensity on an indoor oval (Thialf, Heerenveen, the Netherlands), separated by ~5 min rest. Subjects were equipped with a portable metabolic system (Cosmed K4b$^2$, Rome, Italy) to analyze expired air. Prior to the skating test the gas analyzer was calibrated using room air and a reference gas mixture (16.1% $O_2$ and 4.04% $CO_2$) and the volume transducer was calibrated with a 3-L syringe (Cosmed S.R.L., Rome, Italy). Before the first bout, subjects were instructed to choose a skating velocity that could be sustained for 30-60 min.[9] Before the subsequent bouts, subjects were instructed about their velocity based on RER, as it was intended to maintain RER just below 1.0. So, skating velocity differed between the three bouts. A local position measurement system (lpmSkate3D, Inmotio Object Tracking BV, Amsterdam, the Netherlands) was used to measure position.

*Data analysis*

Based on time and position data, the average skating velocity per lap was determined. Velocity and respiratory data were synchronized in order to calculate average data per lap. Skating economy (in mL $O_2 \cdot kg^{-1} \cdot km^{-1}$) was determined based on the average $\dot{V}O_2$ and skating velocity of lap 6 of each bout. For each subject the exercise bout with a mean RER closest to 1.0, ideally smaller than 1.0, was selected for data analysis.

**Historic data**

A literature search was performed to collect all speed-skating studies in which respiratory data and skating velocity were collected during submaximal skating. This search resulted in a total of seven studies that were identified as relevant for this study.[9,11–16] Based on the individual values or group mean values of body mass, submaximal $\dot{V}O_2$, and skating velocity, skating economy was determined. Di Prampero et al.[12] reported skating economy in their manuscript, so this mean value was used in the current study. Two individual datasets of the above described parameters were obtained from the study of de Koning et al.,[9] in this case the exercise bout with a mean RER closest to 1.0, ideally smaller than 1.0, was selected.[17] In addition, an unpublished dataset collected in 2003/2004 was used (Table 2). The skaters that participated in that study were part of a Dutch commercial team (4 males, 1 female; age men 26 ± 3 yr (mean ± standard deviation, SD), woman 26 yr; height men 182 ± 6 cm, woman 167 cm; body mass men 79.8 ± 6.3 kg, woman 63 kg) and won in total 8 medals at the World Championships Distances of 2003 and 2004 and one medal at the World Allround Championship 2003. During their speed skating careers these five skaters won seven Olympic medals.

**Statistics**

Data are reported as means ±SD. Speed skating economy of the group of contemporary athletes was explored by a boxplot. To evaluate if economy changed over time a linear regression analysis was performed. In the study of Houdijk et al.[14] the same group of skaters skated on both conventional skates and on klapskates. As all the other studies did not perform repeated measurements under different circumstances, the skating measurements performed on klapskates by Houdijk et al.[14] were removed from the analyses. To arrive at an unbiased estimate of the relationship between year of data collection and economy, type of skate (conventional skate or klapskate), rink (outdoor or indoor), altitude (lowland or highland), and method (Douglas bags or Cosmed $K4b^2$) were explored for confounding as well as effect modification. A significant interaction would result in stratified analyses. Confounding was investigated by adding the potential confounder to the univariate model of year in relation to economy. If the regression coefficient of year changed by more than 10%, when adding the potential confounder to the univariate model, the confounder was included in the final regression model.[18] Regression coefficients and their 95% confidence intervals (CI) were determined, as well as the variance explained ($R^2$) by the regression models. Results were considered to be significant if $P < 0.05$.

## Results

### Speed skating economy of contemporary athletes

Average skating velocity and respiratory data during the final lap of the chosen exercise block of the contemporary athletes are presented in Table 1. Skating economy was determined based on these data, which resulted in an average economy of 73.4 ± 6.4 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$. The median and the range of skating economy values are displayed in Figure 1.

### The change in speed skating economy over the years

The study characteristics of the datasets included in the linear regression analysis are summarized in Table 2. In general these datasets were based on data of 5 to 12 skaters, mainly junior skaters active in the national junior teams, competing at international level.

The change in skating economy over the years is displayed in Figure 2. The results of the linear regression model with only year of data collection as independent variable are summarized in Table 3A. This model showed that economy significantly improved ($\dot{V}O_2$ declined) over the years by -0.57 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ each year (95% CI [-0.84, -0.31]). Subsequently, the independent variable of skate type (conventional or klapskate) and the interaction between year and skate type were included in the model, which appeared to be significant. Therefore, subsequent analyses were performed on the data obtained on conventional skates and klapskates separately. The results of the stratified analysis, with only year as independent variable are summarized in Table 3B. The analyses showed that for the era of the conventional skate (<1996), the association between year and skating economy was not significant, but that the association during the klapskate era (>1996) was significant, with an estimated improvement in economy of -0.82 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ each year ([-1.42, -0.22]). Both regression coefficients for year (conventional skate and klapskate era) were further examined for confounding. Due to collinearity with year, type of rink (outdoor or indoor) was not incorporated in the model based on the data obtained on conventional skates (r = 0.996) and method (Douglas bags or Cosmed $K4b^2$) was not incorporated in the model based on the data obtained on klapskates (r = 0.80). In the era of the conventional skates, altitude was not considered a confounder, as the data were only obtained on lowland rinks. Similarly, type of rink was not considered a confounder in the klapskate era. The method with which the respiratory data were obtained was incorporated in the final model as confounder for the conventional skate era, as it changed the regression coefficient of year by more than 10% (Table 3C). In the final regression model for the klapskate era, the altitude at which the ice rink was located was incorporated as confounder (Table 3C), which resulted in an improvement in skating economy of -0.58 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ each year, although this appeared not to be significant ([-1.19, 0.035]).

## Discussion

### Speed skating economy of contemporary athletes

The first goal of this study was to determine speed skating economy in contemporary athletes. In the present study an average economy of 73.4 ± 6.4 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ was found. As mentioned in the methods section, Di Prampero et al.[12] reported skating economy in their manuscript. At a velocity of 10 m/s, comparable to the average speed at which the contemporary athletes in the present study skated (9.54 ± 0.82 m/s), skating economy was 93 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$. So, the skating economy of the contemporary athletes seems substantially better than the economy of the skaters participating in the study of Di Prampero et al.[12] As the skaters participating in the study of Di Prampero et al.[12] were of international level, a difference in competition level and skating experience cannot explain the difference in economy.

**The change in speed skating economy over the years**

The second goal of this study was to evaluate the change in speed skating economy over the years. The main finding of the present study is that economy has significantly improved over the past ~50 years (Table 3A).

Is the change in skating economy also directly supportive of improved performance? If $\dot{V}O_{2max}$ for a mixed sample of elite male and female skaters is 65 mL·kg$^{-1}$·min$^{-1}$, as found during the maximal incremental test performed 6-8 days before the speed-skating test in the contemporary athletes, then a skating economy of 93.6 mL $O_2$·kg$^{-1}$·km$^{-1}$, as in the early historical data of Ekblom et al.,[11] predicts a velocity of 11.6 m·s$^{-1}$ or a finish time of 2:10 (min:s) on the 1500 m. This finish time is in between the 1500-m world records of Ard Schenk 2:05.3 (January 1966) and Inga Artamonova 2:19.0 (January 1962). An economy of 81.5 mL $O_2$·kg$^{-1}$·km$^{-1}$, as obtained on klapskates in the studies of de Koning et al.,[9,13] predicts a velocity of 13.3 m·s$^{-1}$ or 1:53 for 1500 m, which is in between the first 1500-m world records skated on klapskates (KC Boutiette 1:50.09, March 1997; Catriona LeMay-Doan 1:57.87, November 1997). Finally, an economy of 73.4 mL $O_2$·kg$^{-1}$·km$^{-1}$, as in the contemporary skaters, predicts a velocity of 14.8 m·s$^{-1}$ or 1:42, which is in between the current 1500-m world records of Shani Davis 1:41.04 (December 2009) and Cindy Klassen 1:51.79 (November 2005). All of these times are within the limits of reality for competitive performances in the respective historical epochs. However, it must be mentioned that these finish times were obtained by assuming that $\dot{V}O_{2max}$ is reached instantaneously and all metabolic energy is provided by the aerobic energy system, which is not the case in reality.[19]

As stated in the introduction, skating economy is an alternative measure of efficiency. Skating economy may be improved over the past ~50 years due to an improvement in efficiency (more mechanical power output delivered fro the same metabolic power input), but can also be improved because of a reduction in power losses (see Figure 3). Unfortunately, data regarding the exact power losses during the experiments, based on which economy is determined, is missing.

Correcting the change in speed skating economy over the years for technological innovations, like the method with which respiratory data is collected (affecting frontal area, see Figure 3), and environmental conditions, like altitude (affecting air density, see Figure 3), resulted in an estimate of the association between year and economy due to athletic improvement. However, it must be mentioned that although economy data have been corrected for several technological and environmental conditions that affect the power needed to overcome air frictional forces, we did not correct for differences in ice friction coefficient that affect the power needed to overcome ice frictional forces. Although possible differences in ice friction coefficient could substantially affect skating economy, the ice friction coefficient during the different experiments has not been measured or reported, so economy data can simply not be corrected for differences in ice conditions. The stratified regression analysis showed that in the era of the conventional skate, after correcting for method with which the respiratory data were obtained, skating economy was not significantly associated to year. In the klapskate era, after correcting for the altitude at which the rink is located, skating economy improved -0.58 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$ each year, which approached significance ($p$ = 0.063). In the klapskate era, the introduction of special skate blades made from powdered metallurgic material (mid-1990s) reduced the ice friction coefficient from 0.0035 to 0.0025,[1] a decline that can explain an improvement in skating economy of 2.87 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$. As the introduction of these skate blades took place at the beginning of the klapskate era, around the time of the measurements of de Koning et al.,[13] this final decline in the ice friction coefficient is not expected to have influenced the improvement in economy during the klapskate era. After correcting for several technological innovations, skating economy did not significantly improve in both the conventional skate and klapskate era Part of this might be due to the relatively low number of speed skating studies conducted, in which velocity and submaximal $\dot{V}O_2$ were determined. Especially in the klapskate era, in which the regression coefficient of year approached significance, we expect that a lack of power restrained the analyses from reaching significance and that economy probably improved over the years, due to athletic improvement. Improved training methodologies, such as a better understanding of concurrent training,[20] improved skating technique attributable to an increased number of hours skating in practice after the advent of indoor ovals in 1987,[21–23] and a change in training intensity distribution,[24,25] might have resulted in an improvement in skating economy and therefore in performance improvement.

As far as we know, this study is the first to evaluate the change in economy of a cyclic sport over multiple decades. Several studies have shown that running economy can be improved by specific interventions over a short period of time,[26] for example 6 weeks of uphill interval training,[27] 4 weeks of familiarization to barefoot running,[28] or 6 weeks of concurrent strength and endurance training.[20] In addition, case studies have shown that cycling efficiency[29] and running economy[30] can improve substantially during an athletic career. However, from the current literature it remains unknown if different modifications in training strategies and in equipment over the years resulted in an improvement in economy over different athletic generations. Besides, both technological innovations and environmental conditions, and athletic improvement contributed to the progression of economy/efficiency. The uniqueness of this study is that we tried to separate these effects. So, the corrected regression coefficient for year reflects an estimate of the association between year and economy, based on athletic improvement. Isolation of the contribution of athletic improvement from the total improvement in economy distinguishes the results of the present study from the above-mentioned studies. This same methodology can be applied to different exercise modalities, like running and swimming, in which it is also (almost) impossible to determine the mechanical power output delivered by the athlete. It is expected that also in running and swimming, economy improved, as the world records in running and swimming also improved substantially.[31,32]

Finally, it must be mentioned that slight differences in the chosen protocol, between the reported studies, could have influenced the economy data. Although the average skating velocity, ranging from 8.97 ± 0.56 m/s to 9.98 ± 0.59 m/s, at which $\dot{V}O_2$ measurements were performed was comparable between studies, it might be that these velocities do not represent the same percentage of maximal aerobic skating velocity. Besides, there might also be differences in training experience and performance level between athletes in the different datasets (Table 2).

## Practical applications

Speed skating performances improved considerably over the past ~50 years and part of this improvement is reflected in speed skating economy as a measure of athletic improvement. So, although we must be cautious when interpreting speed skating economy data, as technological innovations like the introduction of the klapskate and environmental conditions influence skating economy, economy seems to be a robust measure to explain changes in performance and can therefore potentially be used to monitor training progression.

## Conclusions

In conclusion, contemporary athletes showed an average speed skating economy of 73.4 ± 6.4 mL $O_2 \cdot kg^{-1} \cdot km^{-1}$. Furthermore, linear regression analysis showed that skating economy improved over the past ~50 years. However, for the klapskate era, the association between year and economy, due to mainly athletic improvement, only approached significance, possibly due to a lack of power. Therefore, future research is recommended to enlarge the number of datasets available.

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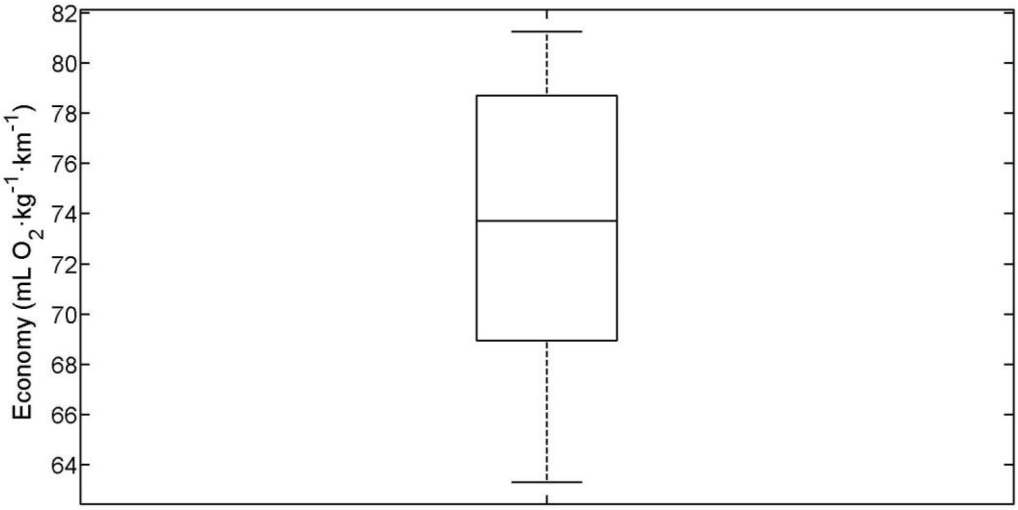


**Figure 1.** Boxplot of the speed skating economy of the contemporary athletes

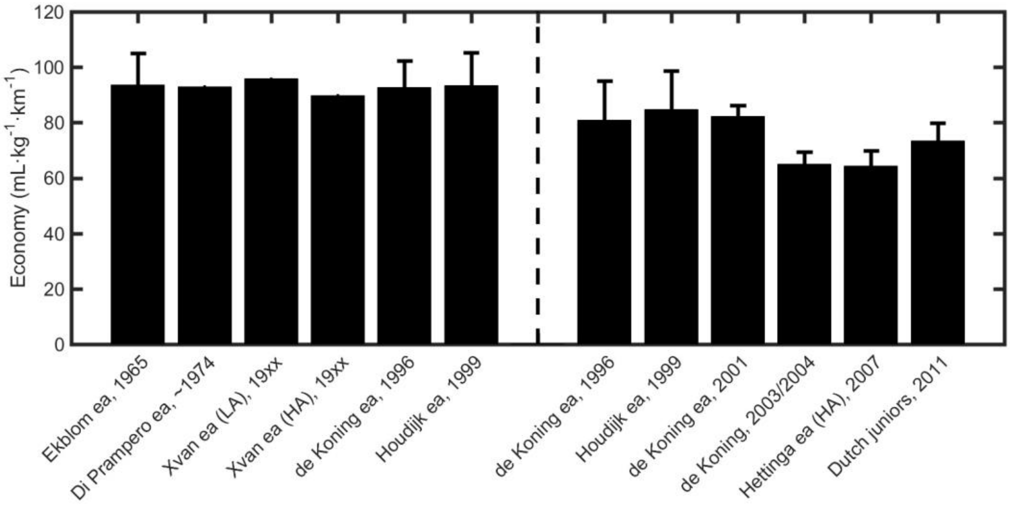


**Figure 2.** Historical improvement in speed skating economy. The datasets to the left of the vertical dashed line are obtained on conventional skates and the datasets to the right of the vertical dashed line on klapskates. Error bars represent the standard deviation.

The year is not the year of publication, but the year of data collection; HA, data obtained on a highland (high altitude) speed skating rink; LA, data obtained on a lowland (low altitude) speed skating rink; CA, contemporary athletes.

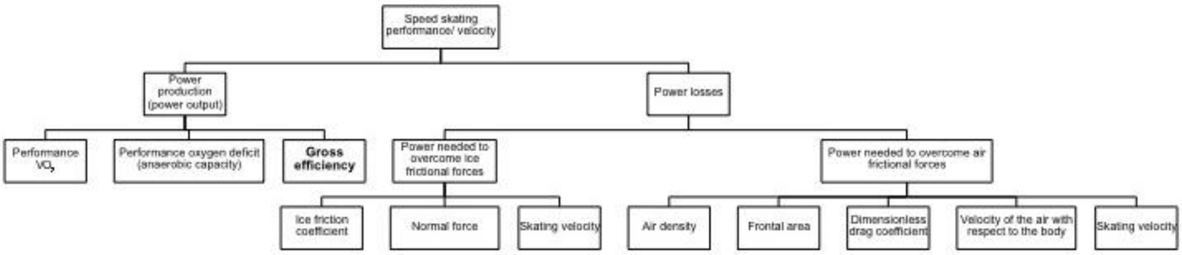


**Figure 3.** Overall schematic of the multiple physiological and biomechanical factors that influence speed skating performance

**Table 1.** Average speed skating velocity and respiratory data during the final lap of the chosen submaximal exercise block of the speed skaters of the Dutch National Junior Team

| **Subjects** | **Skating velocity ($m \cdot s^{-1}$)** | **$VO_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)** |
|---|---|---|
| 1 | 9.60 | 41.7 |
| 2 | 7.68 | 34.5 |
| 3 | 9.40 | 45.1 |
| 4 | 9.73 | 38.4 |
| 5 | 9.99 | 37.9 |
| 6 | 10.0 | 46.6 |
| 7 | 9.50 | 46.3 |
| 8 | 10.4 | 44.9 |
| Mean ± SD | 9.54 ± 0.82 | 41.9 ± 4.5 |

**Table 2.** Study characteristics of the studies included in the linear regression analysis

| Study | Subjects | Year of data collection | Skates (conventional or klapskates) | Ice rink (indoor or outdoor) | Altitude (lowland or highland rink) | Method (Douglas bags or Cosmed K4b[2]) |
|---|---|---|---|---|---|---|
| Ekblom et al.[11] | 6 males | < 1965 | Conventional skates | Outdoor | Lowland | Douglas bags |
| de Koning et al.[13] | 12 male juniors | 1996 | Conventional skates | Indoor | Lowland | Douglas bags |
| Houdijk et al.[14] | 3 male juniors, 3 female juniors | 1999 | Conventional skates | Indoor | Lowland | 4 skaters Douglas bags, 2 Cosmed K4b[2] |
| de Koning et al.[13] | 11 male juniors | 1996 | Klapskates | Indoor | Lowland | Douglas bags |
| de Koning et al.[9] | 6 male juniors, 1 female junior | 2001 | Klapskates | Indoor | Lowland | Cosmed K4b[2] |
| de Koning (unpublished data) | 1 female, 4 male seniors | 2003/2004 | Klapskates | Indoor | Lowland | Cosmed K4b[2] |
| Hettinga et al.[15] | 7 male young seniors | 2007 | Klapskates | Indoor | Highland | Cosmed K4b[2] |
| Dutch National Junior Team | 4 male juniors, 4 female juniors | 2011 | Klapskates | Indoor | Lowland | Cosmed K4b[2] |

**Table 3.** Results of the linear regression analysis, performed to assess if economy (y) changed over time (year, x)

| | | | |
|---|---|---|---|
| **A** | | | |
| | b | SEb | 95% CI |
| Constant | 1225.1* | 266.3 | 692.7, 1757.5 |
| Year | -0.57* | 0.13 | -0.84, -0.31 |
| **B** | | | |
| | b | SEb | 95% CI |
| **Conventional skate** | | | |
| Constant | 134.1 | 303.1 | -494.4, 762.6 |
| Year | -0.021 | 0.15 | -0.34, 0.30 |
| **Klapskate** | | | |
| Constant | 1718.2* | 596.9 | 508.7, 2927.8 |
| Year | -0.82* | 0.30 | -1.42, -0.22 |
| **C** | | | |
| | b | SEb | 95% CI |
| **Conventional skate** | | | |
| Constant | 30.5 | 292.8 | -578.4, 639.4 |
| Year | 0.039 | 0.15 | -0.27, 0.35 |
| Method | -13.9 | 7.45 | -29.3, 1.64 |
| **Klapskate** | | | |
| Constant | 1240.6* | 602.8 | 18.1, 2463.0 |
| Year | -0.58 | 0.30 | -1.19, 0.035 |
| Altitude | -9.51* | 4.15 | -17.9, -1.08 |

Constant, constant (intercept) of the regression equation. Note: A, $R^2 = 0.23$; B conventional skates, $R^2 = 0.001$; B klapskates, $R^2 = 0.17$; C conventional skates, $R^2 = 0.14$; C klapskates, $R^2 = 0.28$; *, $p < 0.05$