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The influence of pole length on performance, O_2-cost and kinematics in double poling

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Abstract

Purpose: In the double poling cross-country skiing technique, the propulsive forces are transferred solely through the poles. The aim of the present study was to investigate how pole length influences double poling performance, O_2-cost and kinematics during treadmill roller skiing. ***Methods:*** Nine male competitive cross-country skiers (24±3 yrs, 180±5 cm, 72±5 kg, VO_{2max} running: 76±6 $mL \cdot kg^{-1} \cdot min^{-1}$) completed two identical test protocols using self-selected (84±1% of body height) and long poles (self-selected + 7.5 cm; 88±1% of body height) in a counter-balanced fashion. Each test protocol included a 5-minute warm-up (2.5 $m \cdot s^{-1}$; 2.5°), three 5-min submaximal sessions (3.0, 3.5 and 4.0 $m \cdot s^{-1}$; 2.5°) for assessment of O_2-cost, followed by a self-paced 1000-m time trial (~3 min, >5.0 $m \cdot s^{-1}$; 2.5°). Temporal patterns and kinematics were assessed using accelerometers and 2D video. ***Results:*** Long poles reduced 1000-m time (mean±90% confidence interval; -1.0±0.7%, $P=0.054$) and submaximal O_2-cost (-2.7±1.0%, $P=0.002$) compared to self-selected poles. The center of mass vertical range of displacement tended to be smaller for long than for self-selected poles (23.3±3.0 vs. 24.3±3.0 cm, $P=0.07$). Cycle and reposition time did not differ between pole lengths at any speeds tested, whereas poling time tended to be shorter for self-selected than for long poles at the lower speeds (≤ 3.5 $m \cdot s^{-1}$, $P \leq 0.10$), but not at the higher speeds (≥4.0 $m \cdot s^{-1}$, $P \geq 0.23$). ***Conclusion:*** Double poling 1000-m time, submaximal O_2-cost and center of mass vertical range of displacement were reduced in competitive cross-country skiers using poles 7.5 cm longer than self-selected ones.

Key words: *Center of mass, cross-country skiers, elite, equipment, exercise economy.*

Introduction

In cross-country skiing, a main sub-technique employed in the classical style is double poling (DP). DP is employed at high speeds where a symmetrical double poling action transfers all propulsive forces solely through the poles.[1] Due to better track preparation and improved equipment a substantial increase in speed has occurred for cross-country skiing races.[2.3] Accordingly, elite male skiers have developed the DP technique and upper-body endurance so they are able to use DP extensively during sprint (≤ 1.8 km, ~3 min), distance (≥ 15 km) and long distance (>50 km) races.

During a DP cycle, the joints are engaged in a sequential pattern prior to and during the poling phase in order to optimize propulsion and transfer potential and rotational energy through the poles as forward kinetic energy.[4-11] Therefore, the pole characteristics are of special interest in DP,[12,13] with pole length being one of the obvious parameters that could influence DP performance. Since the pole length used in a competition needs to be a compromise between the optimal lengths used in the different sub-techniques and terrains, knowledge about the specific effects of pole length on performance would be beneficial to cross-country skiers.

Although the effect of pole length has been widely discussed over several decades, it has received relatively little scientific attention.[14-17] In the early 1990s, the pioneering work by Hoffman et al.[17] found insignificant differences in O_2-cost between long (~ 89% of body height) and self-selected pole lengths (~ 83% of body height) in the DP technique. Later, Nilsson et al.[15] found, by studying ground reaction forces during a DP stroke on a force platform, that poles 7.5 cm longer than self-selected ones induced a longer poling time with higher anterior-posterior reaction forces. Furthermore, Hansen & Losnegard[16] compared self-selected with 7.5 cm longer or shorter poles in an 80-m time trial on snow using the DP technique. They found that the longest poles were faster than self-selected and shorter poles. However, the effect of pole length on endurance performance has not yet been investigated.

Our primary aim was to compare self-selected and 7.5 cm longer poles on performance during an ~3 min trial, O_2-cost and kinematical patterns in the DP technique among competitive cross-country skiers. The main hypothesis was that longer poles would improve exercise economy and subsequently endurance performance compared to poles of self-selected length.

Methods

Subjects

Nine male cross-country skiers (age 24 ± 3 yrs; body height 180 ± 5 cm; body mass 72 ± 5 kg) participated in the study. Their maximal aerobic power during treadmill running was tested on a separate day with mean ± standard deviation values being 76 ± 6 (range: 69-83) $mL \cdot kg^{-1} \cdot min^{-1}$ (for the protocol see Losnegard et al.[18]). Among the skiers there was one participant with several victories in the International Ski Federation (FIS) World Cup, one skier with several top 15 rankings in the World Cup, one skier with several top 10 rankings in Ski Classics and one skier with top 15 rankings in the Norwegian Championships. The remaining five skiers were classified as highly trained regional level skiers. The study was evaluated by the Regional Ethics Committee of Southern Norway, and all subjects gave their written informed consent before study participation.

Design

Prior to testing, the subjects had one familiarization session. The protocol was identical to the main protocol described below. However, on the submaximal loads the subjects switched systematically between their self-selected poles in the classical style (84 ± 1% of body height) and “long poles” (self-selected +7.5 cm; 88 ± 1% of body height). The length of “long poles” was chosen based on previous studies where 7.5 cm increase induced changes in kinematics and performance compared to self-selected poles.[15,16] During familiarization for the 1000-m time-trial, four skiers used self-selected and five skiers used long poles. On two separate days, the subjects completed an identical testing protocol using self-selected and long poles in a counter-balanced fashion. The protocol included three submaximal workloads in the DP technique for assessment of exercise economy (O_2-cost), heart rate (HR) and rating of perceived exertion (RPE; Borg[19]). Thereafter the subjects performed a 1000-m self-paced time trial in DP. Temporal patterns and kinematics were assessed using accelerometers and 2D video.

Methodology

Submaximal and 1000-m tests. Prior to testing, a warm-up consisted of 5 min DP (2.5 $m \cdot s^{-1}$ at 2.5°). Thereafter, the subjects performed three 5-min submaximal bouts using DP (3.0, 3.5 and 4.0 $m \cdot s^{-1}$ at 2.5°) with 2 min breaks between bouts. The speeds and inclines were chosen to induce a competition-relevant technique and to obtain steady-state oxygen uptake. The O_2-cost and heart rate (HR) were determined as the average oxygen uptake and average HR, respectively, from minute 3 through minute 5 in each bout. RPE was reported directly after each workload. After an 8-minute low intensity bout (2.5 $m \cdot s^{-1}$; 2.5°, ~ 60% of peak heart rate; HR_{peak}), subjects performed a 1000-m time-trial test in the DP technique at 2.5°. The speed was fixed at 4.75 $m \cdot s^{-1}$ during the initial 100 m, at 5.0 $m \cdot s^{-1}$ from 100–200 m, and thereafter the speed was self-selected.[18] The highest HR value averaged over 30 s during the test was considered as HR_{peak}. Video recording for analysis of joint angles, pole angles and displacement of center of mass in DP was conducted at 4 $m \cdot s^{-1}$. Accelerometer data from the right pole were obtained during all submaximal loads in the DP technique (2.5, 3.0, 3.5 and 4.0 $m \cdot s^{-1}$) and during the 1000-m time trial to analyse temporal patterns automatically by identifying pole plants and lift-offs.[20]

Apparatus. All roller ski tests were performed on a 3 x 4.5 m treadmill (Rodby, Södertalje, Sweden). VO_{2max} running was measured on a treadmill (Woodway ELG, GmbG, Weil am Rein, Germany). In all tests, oxygen consumption was measured by an automatic ergospirometry system (Oxycon Pro, Jaeger Instrument, Hoechberg, Germany), as evaluated by Foss and Hallén[21]. Heart rate was measured with a Polar S610i monitor (Polar Electro Oy, Kempele, Finland). The skiers used Swix Triac 1.0 poles (Swix, Lillehammer, Norway) with a tip customized for treadmill rollerskiing. All skiers used Swix Triac poles during daily training and competitions. Two different pairs of Swenor Fibreglass rollerskis (Swenor, Sarpsborg, Norway) with wheel type 2 (front) and 3 (rear) were used, depending on the binding system the skiers normally used (NNN, Rottefella, Klokkarstua, Norway or SNS, Salomon, Annecy, France). Prior to testing, the skis were kept in a heating-box at 60°C for 15 min to stabilize the temperature (Swix, Warmbox T007680-110, Lillehammer, Norway). This produced a friction coefficient of 0.026 during testing (for both pairs of skis). Video was captured at a distance of 6.6 meters perpendicular to the skiing direction (Canon, HF100, Tokyo, Japan). White tape, marked with a black dot, was placed at ankle, knee, hip, shoulder, elbow and wrist in order to detect joint centres on the video.

Accelerometer data analysis. An inertial measurement system from PLUX Wireless Biosignals S.A. (Lisbon, Portugal) was mounted on the skiers and was used for detecting right pole plant and lift-off, as previously described.[20] Cycle time (CT) was defined as the time between right pole plants. Poling time (PT) was defined as the time between a pole plant and subsequent pole lift-off, and reposition time (RT) as the time between pole lift-off and subsequent pole plant. For all temporal variables, the average over 10 consecutive cycles was used and the same setup and analyses were performed on all collected data.

Joint kinematics. To determine the right side sagittal joint angles, the 2D videos were converted to 50 Hz using Dartfish Connect 4.5.2.0 (Dartfish, Fribourg, Switzerland) and further analysed using Tracker (Tracker version 4.84, Douglas Brown, Open Source Physics). A calibration stick, representing a length of 232 cm in the center of the treadmill, was marked in each video. Seven reference points (wrist, elbow, shoulder, hip, knee, ankle, and pole tip) were manually marked in each frame during 5 consecutive cycles by a researcher blinded to pole length. For comparison, the coordinates for each cycle were time-normalized using a third order 101 point interpolation, prior to joint angle calculations according to Figure 1. Notice that the ankle angle was calculated from the knee and ankle reference points and the horizontal plane through the ankle joint (Figure 1). The horizontal distance between the pole tip and the ankle joint at pole plant was defined as the forward pole plant.

<<Figure 1 near here>>

The vertical center of mass (COM) was calculated from segmental analysis of six body segments (forearm including the hand; upper arm; trunk and head; thigh; leg; and foot) in addition to separate segments for skis and poles. Based on a standard table,[21] the relative mass of each body segment with respect to the total body mass was calculated and the equipment was weighed independently. The weights of the ski boots were added to the foot segment. Each body segment's COM was calculated with respect to its proximal segmental reference.[22] The COM of the poles and skis were set at 43% of the pole length from the proximal end and at 3 cm behind the binding system, respectively. At each instant of time, the 2-D position (antero-posterior and vertical) of the whole body COM including equipment was calculated as the weighted average of all eight segments' COM [23] and presented as displacement from the whole cycle's average COM position.

Statistical Analysis

Data are presented as mean ± standard deviation (SD) and the relative differences between pole lengths are presented as mean ± 90% confidence interval (CI). The effect of pole length was analysed using the paired Student's t-test procedure for pairwise comparisons. A two-factor within-subject repeated measures ANOVA was used to calculate the global effects of pole length (self-selected vs. long) and speed (3-5 levels; 2.5-5.0 $m \cdot s^{-1}$) on physiological and biomechanical variables in addition to their interaction effects (pole length × speed). In case of significant global differences, post-hoc analyses with the Bonferroni correction for multiple comparisons were conducted to analyse the effect of pole length and velocity separately for each velocity and pole length, respectively. The same type of model was used to analyse the effect of pole length on the mean speed and accumulated time per 100 m during the 1000-m test (2 × 10 design). Statistical calculations were performed with Microsoft Office Excel 2013 (Microsoft, Redmond, Washington, USA) and IBM SPSS Statistics 21.0 (International Business Machines, New York, USA). A P-value ≤ 0.05 was considered statistically significant and P-values ≤ 0.10 were considered tendencies.

Results

1000-m time trial

The 1000-m time was 192.3 ± 14.3 s with self-selected poles and 190.3 ± 13.1 s with long poles, which corresponded to a mean difference (± CI) of 1.0 ± 0.7% ($P = 0.054$; Figure 2A). No significant difference in velocity was found during the first 700 m, but long poles induced a higher speed between 800-900 m ($P = 0.004$). This resulted in a significantly lower accumulated time at 900 m ($P = 0.02$) compared to self-selected poles and this lead was maintained through the last 100 m (Figure 2B). No significant differences were found in average cycle rate (1.02 ± 0.05 for both pole lengths, $P = 0.83$) or average cycle length (5.37 ± 0.43 vs 5.43 ± 0.39 m, $P = 0.52$) between self-selected and long poles, respectively. In addition, no significant differences in PT or RT during the 1000-m time trial were found between pole lengths (average PT of 0.32 ± 0.02 s and RT of 0.67 ± 0.02 s for both pole lengths). Peak heart rate did not differ between long and self-selected poles (184 ± 13 vs 185 ± 10 beat·min^{-1}, $P = 0.60$).

<<Figure 2 near here>>

Submaximal tests

Long poles resulted in a significantly lower O_2-cost at all speeds (3.0 - 3.5 - 4.0 m·s^{-1}), with an overall mean difference (±CI) of -2.7 ± 0.7 % ($P = 0.002$) compared to self-selected poles (Figure 3). No significant differences were found in overall heart rate (-1.0 ± 2.7 %, $P = 0.47$) or RPE during the submaximal loads (-2.1 ± 2.6 %, $P = 0.23$) for long compared to self-selected poles. No interaction was found between speed and pole length in the O_2-cost, HR or RPE (P = 0.28-0.83).

<<Figure 3 near here>>

Cycle time, PT and RT from 2.5-5.0 m·s^{-1} (steady state speeds) for long and self-selected poles, respectively, are shown in Figure 4. Overall, for these speeds, no significant differences were found for CT or RT. Poling time showed a tendency towards an overall difference between pole lengths ($P = 0.08$) and a non-significant interaction (speed x pole length; $P = 0.15$). Post-hoc analyses showed that PT tended to be longer for long compared to self-selected poles at 2.5 - 3.5 m·s^{-1} (~ 0.02 s, $P \leq 0.10$), while no significant differences were found at 4 m·s^{-1} ($P = 0.23$) and 5 m·s^{-1} ($P = 0.59$). The pole angle, relative to horizontal, was not significantly different between pole lengths during the poling thrust. However, at pole plant, the pole tip was planted slightly, but not significantly, further forward relative to the ankle joint with self-selected compared to long poles (55 ± 9 vs 51 ± 10 cm, $P = 0.11$).

<<Figure 4 near here>>

The vertical elevation of COM (zCOM) from the lowest (~ 29% of CT) to the highest point (~ 92% of CT) tended to be smaller in long versus self-selected poles (23.3 ± 3.0 vs. 24.3 ± 3.0, $P = 0.07$, Figure 5).

<<Figure 5 near here>>

The joint angle analysis at 4 $m \cdot s^{-1}$ during a full DP cycle is shown in Figure 6. The hip and ankle were more extended during the entire poling phase ($P < 0.001$), knee angle was more extended at the start of poling phase ($P = 0.01$) for long than self-selected poles, while shoulder, elbow and pole angles were not different between pole lengths. No significant differences were seen in hip joint angle from the start of RT to the following hip flexion (~ 85% of CT). Thus, the hip range of motion (ROM) was significantly smaller for long vs self-selected poles during a full cycle (81 ± 11 vs. 84 ± 10°, $P = 0.02$). Shoulders were slightly more extended at the start of the shoulder flexion (~50% of CT) with long versus self-selected poles. During this period, the elbows were more flexed whereas prior to pole plant (83-95% of CT), the elbows tended to be more extended for long than for self-selected poles (all $P < 0.10$).

<<Figure 6 near here>>

Discussion

This study investigated how pole length influenced performance, O_2-cost and kinematics during DP while treadmill roller skiing. The principal findings were: (I) 7.5 cm longer than self-selected poles improved 1000-m time and reduced submaximal O_2-cost. (II) Vertical displacement of COM during a cycle was smaller in long versus self-selected poles. (III) Cycle time did not differ between pole lengths at any speeds tested, whereas PT tended to be shorter for self-selected than long poles at the lower speeds ($\leq 3.5\ \mathrm{m \cdot s^{-1}}$), but not at the highest speeds ($\geq 4\ \mathrm{m \cdot s^{-1}}$).

Already in 1990, Hoffman et al.[14] proposed that *"...it appears that the length of the ski poles may be an important determinant for the economy of the double poling technique."* Since then, a few previous studies have studied the influence of pole lengths on kinematics, O_2-cost and/or short term performance in DP.[15-17] However, the present study demonstrates for the first time that longer pole length improve endurance performance and reduce the O_2-cost during DP.

Coinciding the improved DP economy and performance using long poles found here, our skiers were able to maintain a higher vertical COM position during the entire poling phase and their vertical COM displacement was smaller than with self-selected poles. As the upper body has been calculated to represent ~ 67% of the body mass in elite cross-country skiers,[23] considerable work is done by the muscles in the lower limbs in order to extend the upper body to an upright position during the reposition phase.[5,8-10] This is also supported by a previous study that associated high-level skiers` superior exercise economy compared to slower skiers with such a biomechanical strategy.[11] Altogether, our findings imply that less up-and-down vertical movement of the COM during the cycle is beneficial for reducing the O_2-cost and maybe even for performance in DP.

The speed differences between pole lengths were only evident during the latter part of the 1000-m test. Thus, longer poles may be particularly beneficial for improving skiers' finishing abilities. However, the reasons for this and whether our findings also apply to actual competitions on snow needs to be elucidated, along with the related mechanisms.

In the present study, CT was unaffected by pole length at all speeds, which has also been found on snow at high speeds previously.[16] At low speeds ($\leq 3.5\ m \cdot s^{-1}$), long poles resulted in a longer relative PT, which has previously been linked to a higher anterior-posterior impulse in DP at similar speeds ($3.92\ m \cdot s^{-1}$).[15] However, the differences in PT between self-selected and long poles decreased as speeds increased, with an almost identical PT between poles at $5.0\ m \cdot s^{-1}$. Further, no systematic differences in cycle rate, cycle length, PT or RT were found between pole lengths during the 1000-m test, which also implies that the higher speed achieved using long poles over the last 200 m was influenced by individual strategies. Hence, it appears that the differences in performance and O_2-cost between pole lengths are not due to variations in temporal patterns.

The present study solely investigated how different pole lengths influence performance and O_2-cost during DP roller skiing. Our results can, hence, not be directly extrapolated to other skiing techniques. A previous study by Stöggl et al.[23] found that the fastest skiers during a short performance test employed relatively longer pole lengths (% of body-height) than their slower competitors, and proposed that longer poles could even be advantageous in the DIA. However, the study by Stöggl et al.[23] was done while roller skiing on a treadmill that may set different demands to kick phase compared to on-snow-skiing. In roller skiing, the rear wheel is locked whereas on snow the ski needs to be compressed towards the snow to obtain grip while skiing.[24] From a practical point of view, the arm movement ("low shoulder") in the reposition phase is of great importance in order to lower the COM and compress the ski's chamber (with kick wax) to the snow to obtain high static friction and thus allow for effective propulsion by the legs. Whether this way of moving is restricted during on-snow-skiing in DIA with long poles needs to be further studied.

In this study, the overall goal was to investigate if increased pole length influence DP performance and not to propose the optimal pole length. As previously suggested, it appears reasonable to assume that an inverted U-shape curve exist between pole length and performance in DP.[16] Furthermore, the present study indicates that the O_2-cost between pole lengths is not influenced by DP speed, at least not with the speeds and incline tested here. Still, the O_2-cost with different pole lengths may respond differently between DP on uphill versus flat terrain. In the study by Hoffman et al.[17], no significant effect on O_2-cost was found between self-selected and long poles at 1° incline whereas our study found reduced O_2-cost with longer poles at 2.5°. Therefore, possible differences between pole lengths' influence on performance at different inclines and external conditions (e.g., roller skiing vs skiing on various snow conditions) sorely need to be better understood.

Practical Application

In the present study, competitive cross-country skiers performed better with 7.5 cm longer poles than their self-selected ones during an ~ 3 min rollerski test in the DP technique. Hence, we recommend competitive skiers to consider whether longer poles could be beneficial for their performance. Furthermore, longer poles resulted in a lower O_2-cost compared with poles of self-selected lengths, potentially caused by a reduced vertical displacement of COM. This implies that less up-and-down vertical movement of the COM during the cycle may be beneficial in terms of reducing the O_2-cost and improving performance during DP. However, the present study only investigated how 7.5 cm longer poles affected roller skiing performance and future research is warranted to examine these aspects on snow in a competitive situation and explore the factors related to optimal pole lengths for individual skiers.

Conclusion

Double poling 1000-m time, submaximal O_2-cost and center of mass vertical range of displacement were reduced in competitive cross-country skiers using poles 7.5 cm longer than self-selected ones.

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Conflict of Interest. No conflicts of interest, financial or otherwise, are declared by the authors.

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Figure legends.

Figure 1: Illustration of the examined joint angles. A = elbow, B = shoulder, C = hip, D = knee, E = ankle. Ankle joint angle was calculated from the following reference points: knee, ankle and the horizontal plane through the ankle joint.

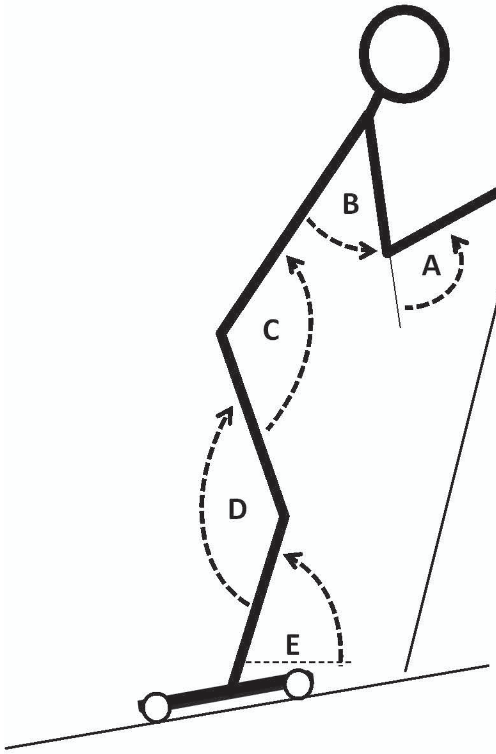
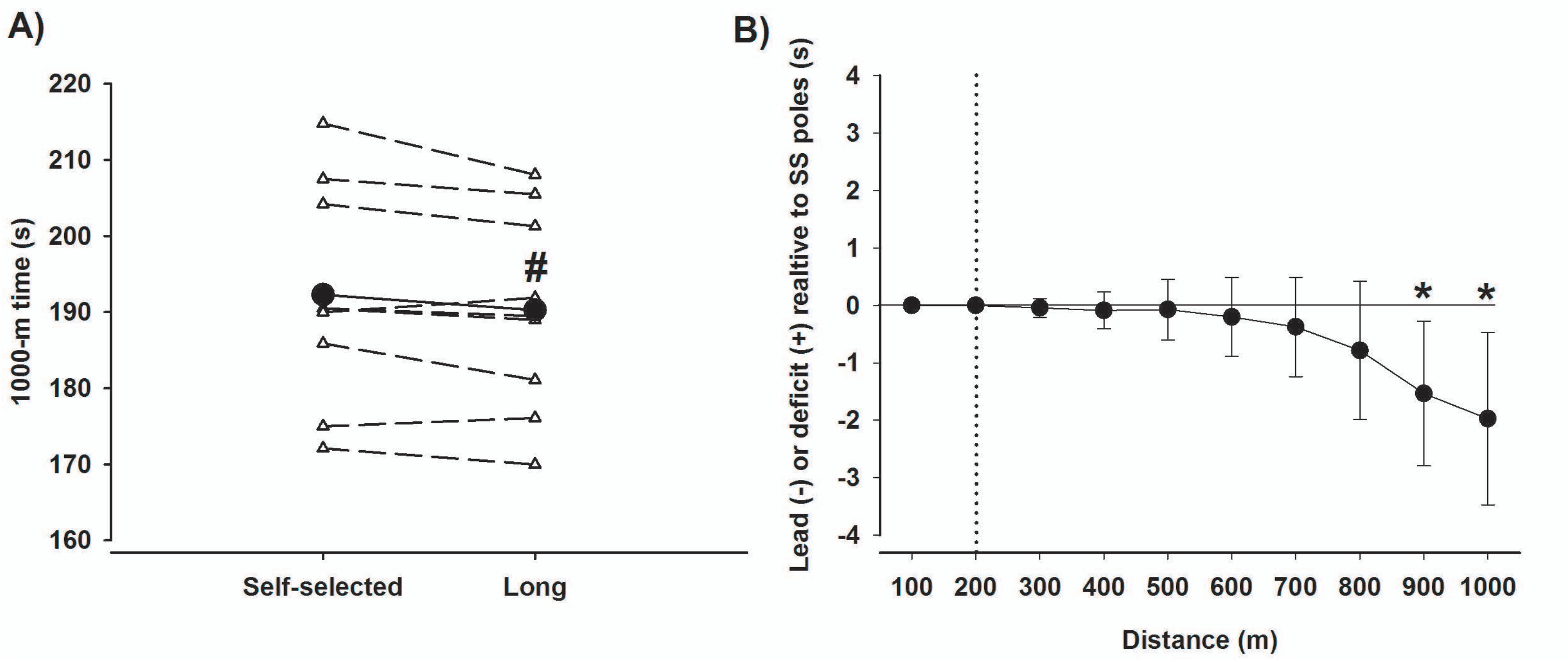


Figure 2: A) Individual (dotted lines with triangle symbols) and mean (full line with circle symbols) 1000-m times during double poling. B) Mean (±90%CI) improvement in performance, presented as lead (-) or deficit (+) for long compared to self-selected (SS) poles during the 1000-m time. During the first 200 m, the speed was set equal for all tests. * Significant differences between self-selected and long poles (+7.5 cm) ($P < 0.05$, $N = 9$). # Tendencies between self-selected and long poles (+7.5 cm) ($P < 0.10$, $N = 9$).


A)
1000-m time (s)
220
210
200
190
180
170
160
Self-selected
Long
#
B)
Lead (-) or deficit (+) realtive to SS poles (s)
4
3
2
1
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-1
-2
-3
-4
100
200
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400
500
600
700
800
900
1000
Distance (m)
*
*

Figure 3: Individual differences in O_2-cost between self-selected and long poles at 3.0, 3.5 and 4.0 m·s^{-1}. Horizontal full lines indicate mean differences and horizontal dotted lines upper and lower 90% CI (*N* = 9).

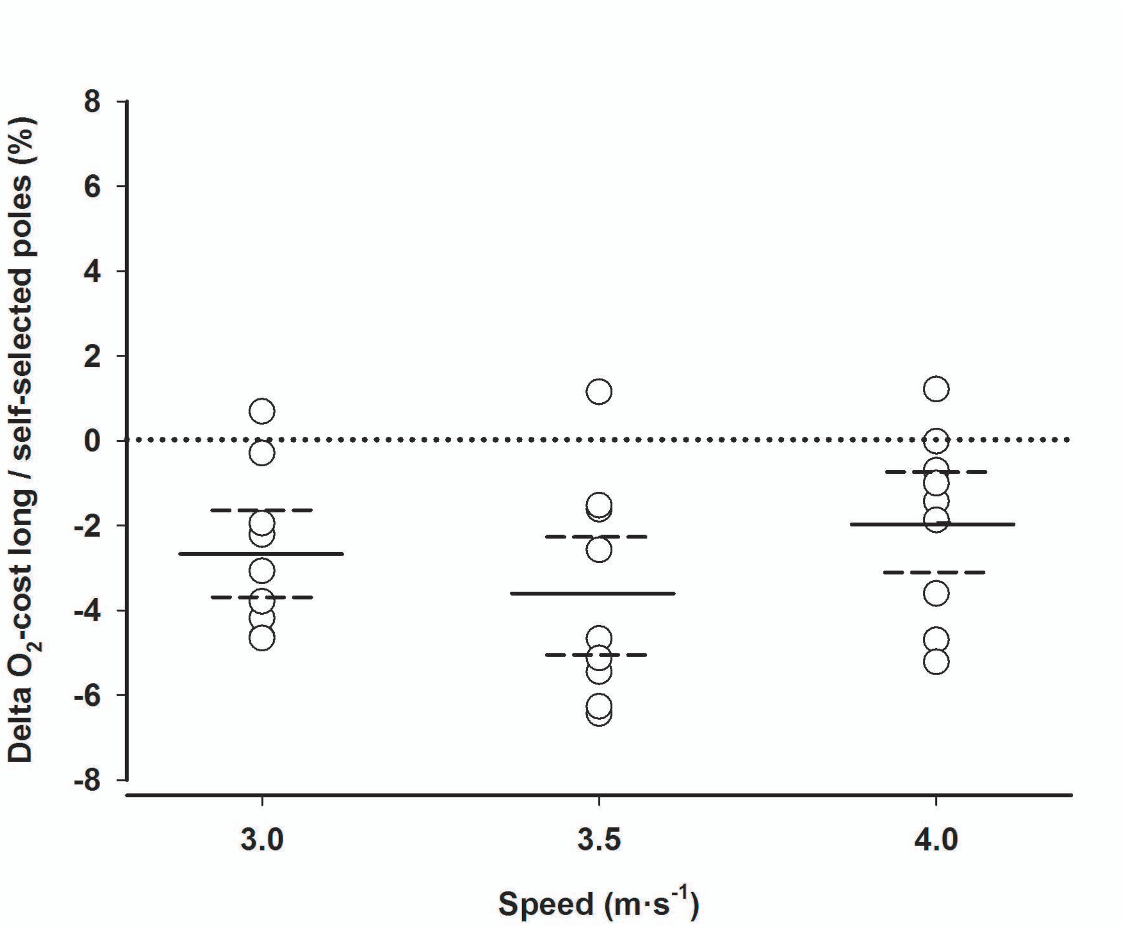
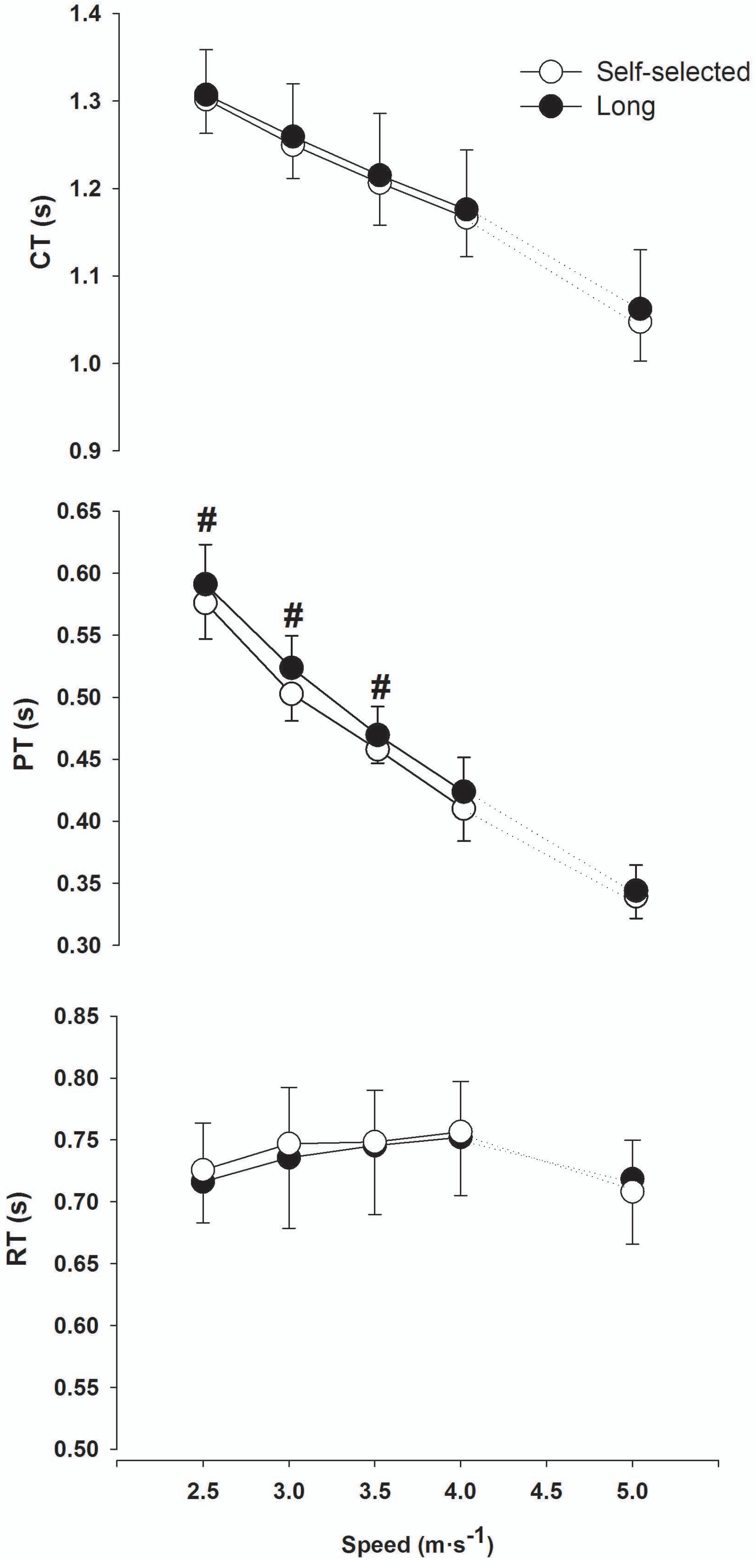


Figure 4: Temporal patterns for self-selected and long poles (+7.5 cm) from 2.5 to 5.0 $m \cdot s^{-1}$ during double poling. Upper panel; cycle time (s), middle panel; poling time (s), and lower panel; reposition time (s). Error bars (standard deviation) for self-selected poles have a negative direction and for long poles a positive direction. # Tendencies between self-selected and long poles (+7.5 cm) ($P < 0.10$, $N = 9$).



1.4
1.3
1.2
1.1
1.0
0.9
CT (s)
Self-selected
Long
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
PT (s)
#
#
#
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
RT (s)
2.5
3.0
3.5
4.0
4.5
5.0
Speed (m·s-1)

Figure 5: Vertical displacement of COM (*z*COM) during a full cycle at 4.0 $m \cdot s^{-1}$ during double poling for self-selected and long poles (+7.5 cm). Each curve represents an average of 5 cycles for each subject. The cycle starts (0%) and ends (100%) at pole plant. The horizontal full line shows the area of differences between the self-selected and long poles (paired t-test, $P < 0.05$, $N = 9$). The upper panel shows a kinegram of a full cycle for self-selected and long poles (+7.5 cm) at 4.0 $m \cdot s^{-1}$ during double poling. Each stick figure represents an average of 5 cycles per subject ($N = 9$).

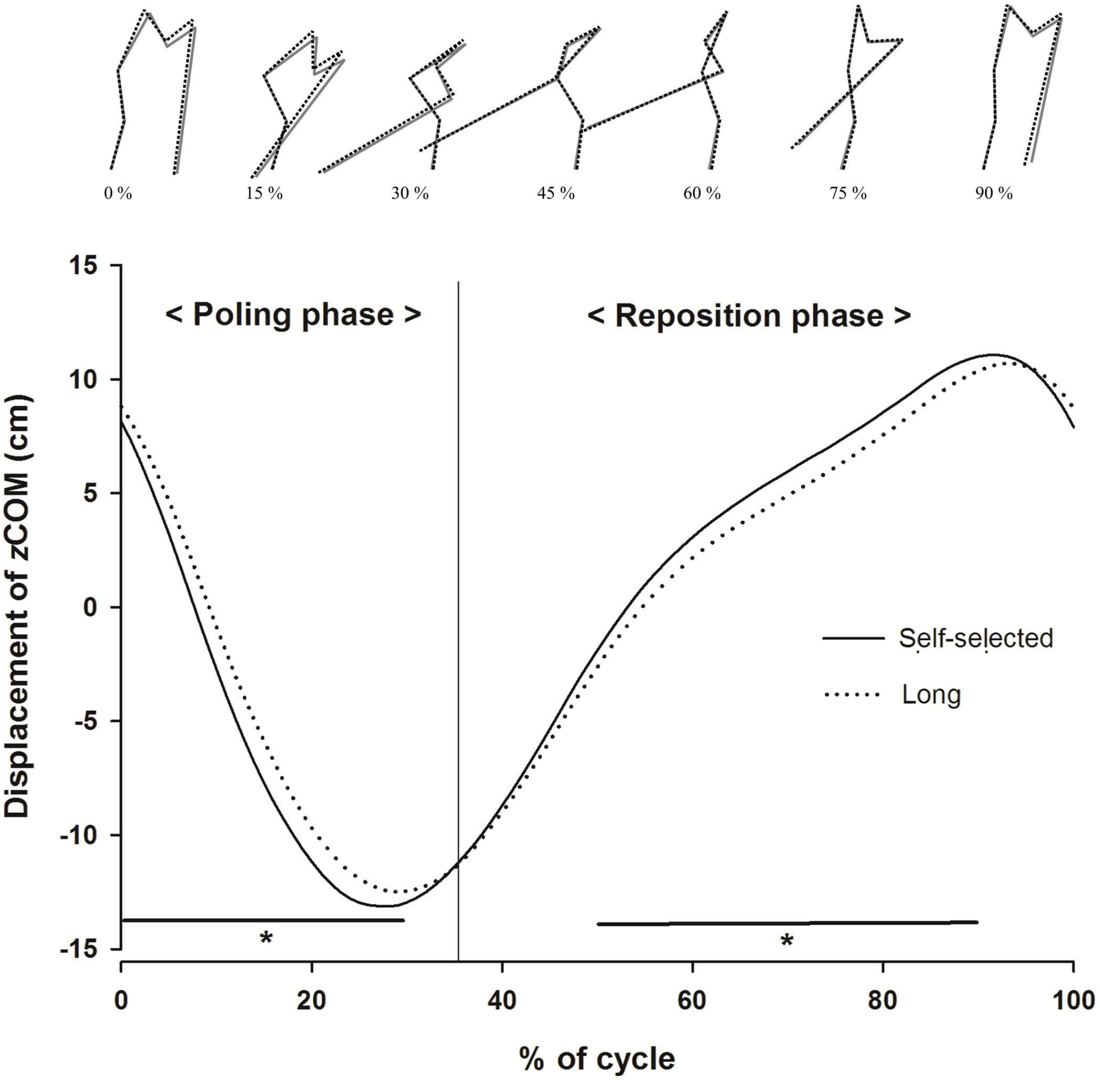
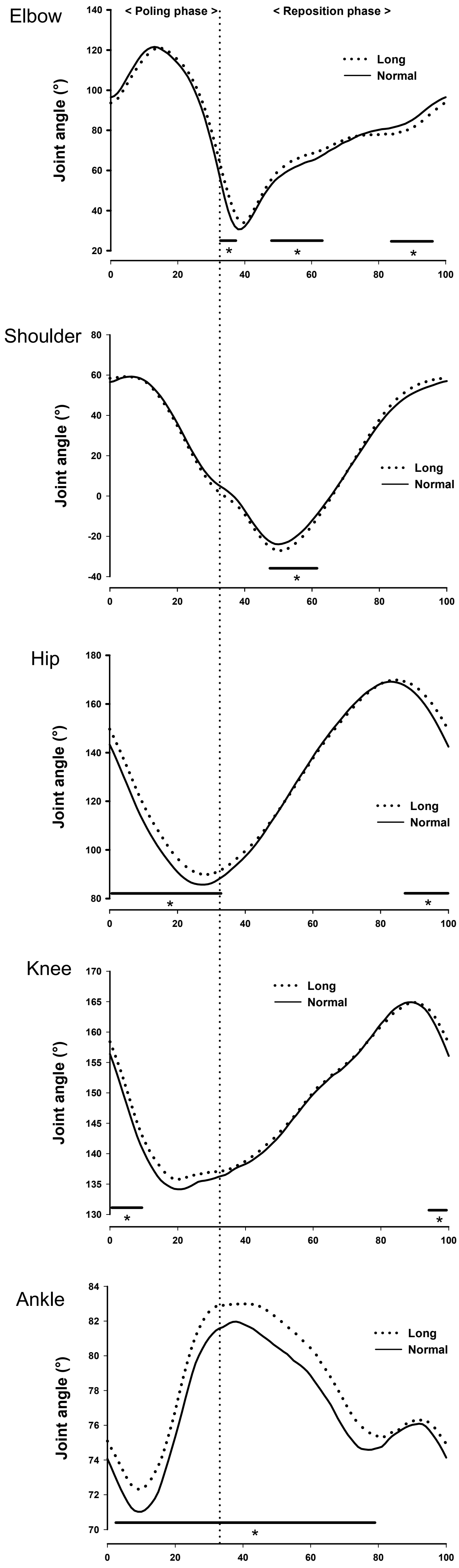

0 %
15 %
30 %
45 %
60 %
75 %
90 %
< Poling phase >
< Reposition phase >
Displacement of zCOM (cm)
15
10
5
0
-5
-10
-15
Self-selected
Long
*
*
0
20
40
60
80
100
% of cycle

Figure 6: Mean joint angle characteristics for the elbow, shoulder, hip, knee and ankle during a full cycle at 4.0 $m \cdot s^{-1}$ during double poling with self-selected and long poles (+7.5 cm). The cycle starts (0%) and ends (100%) at pole plant. The horizontal full line shows the area of differences between the self-selected and long poles (paired t-test, $P < 0.05$, $N = 9$).


Elbow
< Poling phase >
< Reposition phase >
Long
Normal
Joint angle (°)
140
120
100
80
60
40
20
*
*
*
0
20
40
60
80
100
Shoulder
Joint angle (°)
80
60
40
20
0
-20
-40
Long
Normal
*
0
20
40
60
80
100
Hip
Joint angle (°)
180
160
140
120
100
80
Long
Normal
*
*
0
20
40
60
80
100
Knee
Joint angle (°)
170
165
160
155
150
145
140
135
130
Long
Normal
*
*
0
20
40
60
80
100
Ankle
Joint angle (°)
84
82
80
78
76
74
72
70
Long
Normal
*
0
20
40
60
80
100
% of cycle