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Differences between elite, junior and non-rowers in kinematic and kinetic parameters during ergometer rowing

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ABSTRACT

This paper presents an analysis of the rowing parameters of differently skilled rowers. The study focuses on technique dependency on stroke rate. Five elite, five junior and five non-rowers participated, and the biomechanics of rowing on an ergometer was analyzed at stroke rates of 20, 26 and 34 str/min. The results show that elite rowers use a similar, consistent rowing technique at all stroke rates, the technique of junior rowers follows similar principles, while the technique of non-rowers varies. Elite rowers' stroke length, handle motion and body posture do not change with stroke rate while the ratio of stroke phases, maximum forces, stroke work and joint loadings are constant at the same stroke rate but dependent on stroke rate. Junior rowers with stroke rate change also the stroke length. In non-rowers the differences can be observed in the handle motion and body posture during the stroke, their stroke length changes with stroke rate while the ratio of stroke phases stays constant. Although different movement execution is evident and variable with stroke rate, non-rowers demonstrate a consistent pattern at the same stroke rate. On the basis of the results, the crucial parameters that differentiate elite, junior, and non-rowers are identified.

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1. Introduction

Ergometer rowing is a complex motor skill. A rower must have a good command of technique, timing, and power. Rowing ergometers can be found in most gyms and fitness centers, but many people who use them have little or no instruction in rowing technique. Rowing is a cyclical movement like running or cycling. However, unlike cycling and running, the rowing stroke cycle is not an intuitive act. Kazunori, Motoshi, Zavatsky, and Halliday (2004) showed that novices have some potentially important differences in technique and warned that faulty technique can lead to injuries. Injuries as a result of faulty technique include problems in the lower back, ribs, shoulder, wrist and knee (Rumball, Lebrun, Di Ciacca, & Orlando, 2005).

A novel approach for training both novice and elite rowers incorporates real-time feedback providing quantitative information about rowing kinematic and kinetic parameters (Henry, Clark, McCabe, & Vanderby, 1995; MacFarlane, Edmond, & Walmsley, 1997).

Different instrumented measurement and training setups for assessing biomechanical parameters of ergometer rowing have been developed in the past. The system developed by Rosow (1991) enables measurements of seat displacement, handle displacement, hip angle, force on handle and footstretcher forces and torques. The system developed by Pudlo, Pinti, and Lepoutre (2005) enables quantification of internal forces and articular moments using the inverse dynamics method. Both of these systems allow only offline data processing. The system of Hawkins (2000) provides offline information about the rower's joint kinematics, pulling force, and pulling power. The system developed by Page and Hawkins (2003) displays rowers' body movement in real-time in the form of two-dimensional stick figure animation. Baca and Kornfeind (2008) have developed a system that provides real-time visual feedback about pulling forces and coordination of double rowing on an ergometer. The system developed by Fothergill (2010) provides real-time feedback on handle trajectory, handle force curve and each foot's force curve. Černe, Kamnik, and Munih (2011) have developed an instrumented rowing ergometer system that enables measurements of kinematic and kinetic parameters, calculation of internal forces and joint moments, and preparation of data for real-time feedback.

On the basis of acquired and available real-time data, we propose a training platform for learning rowing technique on an ergometer. The platform consists of a measurement module, a data processing module, a reference module and a module for feedback information. The measurement module provides kinetic and kinematic data of the rower. The data are processed in the data processing module that calculates body joint loadings and provides quantification of biomechanical parameters. The essence of the reference module is a reference model of biomechanical parameters that describes proper ergometer rowing technique. The reference module evaluates processed data by comparison between real-time data and reference data. Based on this assumption, a module for feedback information determines the needed instructions and outputs graphical and audio information to the trainee rower. According to the feedback information the rower modifies movement towards proper ergometer rowing technique.

For development of the reference model, a proper set and proper range of values of input variables should be found. A wide range of biomechanical parameters can be measured during ergometer rowing. The question is which of those parameters are effective for feeding back and describing the rowing technique. Redgrave (1995) and Nolte (2005) described the basic biomechanical parameters that characterize ergometer rowing technique: the stroke length, the duration and ratio of the stroke phases, the forces of the stroke on the handle and foot stretcher, the power of the stroke, the trajectory of the handle motion, the body posture and the body joint loads. Some of those parameters are dependent on stroke rate. Kleshnev (2003) demonstrated that the ratio of the drive and recovery time of stroke is dependent on stroke rate. McGregor, Bull, and Byng-Maddick (2004) investigated spinal and pelvic motion, and the force generated at the handle at three different stroke rates. They showed that there is no change in the magnitude peak of spinal torque generated during different stroke rates, but a shift in the instant of occurrence was noticed. They also showed changes in pelvic rotation at the catch and finish of the stroke.

This paper addresses the search for rowing parameters that characterize the ergometer rowing technique. The goal of the study was to investigate the differences between elite, junior and non-rowers in order to identify parameters that have the potential to be incorporated in the reference model, their range of values and consistency regarding stroke rate. With this objective, we analyzed technique of ergometer rowing of 5 elite rowers, 5 junior club rowers and 5 non-rowers. In the following section, the participants, apparatus, experimental protocol, variables, data processing and statistical analyses are presented. The third section outlines the results; conclusions are drawn in the fourth section.

2. Methods

2.1. Participants

Fifteen volunteers (male, Caucasian) participated in the study: (a) five elite rowers (age from 22 to 38 years, mean = 30.4 years; height from 186 to 197 cm, mean = 191,6 cm; weight from 84 to 100 kg, mean = 89 kg), who are members of the National Rowing Team and holders of World Championship medals, (b) five junior rowers (age from 15 to 18 years, mean = 16.7; height from 179 to 188 cm, mean = 183 cm; weight from 75 to 100 kg, mean = 82.4 kg), who are training rowing in an organized program on club level, and (c) five non-rowers (age from 25 to 32 years, mean = 28 years; height from 171 to 188 cm, mean = 182,8 cm; weight from 76 to 100 kg, mean = 84,6 kg), who were introduced to a rowing ergometer for the first time. The non-rowers represented a group of people beginning rowing for recreation without any basic teaching and professional supervision. All participants provided consent.

2.2. Apparatus

We used a measurement system for rowing assessment on an ergometer developed by Černe et al. (2011). The measurement system consists of a Concept2 rowing ergometer instrumented with a load cell for measuring the force of arm pull, a six-dimensional force sensor for measuring the force of leg drive, an optical encoder for measuring the length of a chain pull and a wire optical encoder for measuring the position of the seat. The optical system Optotrak Certus was used for measuring the kinematics of the rower's movement. Fourteen active markers were attached to the rower's body and

Fig. 1. Rower during measurement track in measurement setup with active markers M1-M14.

ergometer as shown in Fig. 1. A video camera was incorporated into measurement setup to visually capture the rower's motion. To follow interaction forces and moment in the rowers' body, joint loadings were calculated according to the recursive Newton-Euler inverse dynamics approach for ankle, knee, hip, lumbosacral and shoulder joints (Sciavicco & Siciliano, 2001). The Newton-Euler inverse dynamics approach determines the joint reaction for the distal segment which is in contact with the environment and proceeds recursively toward the proximal segments. The forces and torques of the lower body segments were thus calculated consecutively from the foot to the reactions acting to the pelvis segment in the hip joints, while the forces and torques of the upper body segments were calculated from the hands to the reactions acting to the pelvis segment in the LS joint (Černe et al., 2011). In this way, all body joint loadings were determined without the need for measuring the seat reactions. Incorporation of seat reaction force measurement would enable the calculation of the LS joint loadings from two different directions along upper and lower extremities thus providing more accurate information.

2.3. Experimental protocol

Each subject's measurement test consisted of three types of activity; each had a defined stroke rate according to typical training procedure: an aerobic type activity at a rate of 20 strokes/minute, an aerobic threshold activity at 26 strokes/minute and an anaerobic activity at 34 strokes/minute. Measurement test started after the steady state situation was reached at each stroke rate. Rowers rowed one minute at a stoke rate of 20 strokes/minute, 30 seconds at 26 strokes/minute and 30 seconds at 34 strokes/minute. The experiment was approved by the National Medical Ethical Committee.

2.4. Variables

We have assumed the symmetry of rowing on ergometer and studied rowing in sagittal plane alike in previous studies (Consiglieri & Pires, 2009; Hahn, Schwirtz, & Huber, 2005; Hase, Andrews, Zavatsky and Halliday, 2002; Hase, Kaya, Zavatsky, & Halliday, 2004; Hawkins, 2000; McGregor et al., 2003; Page & Hawkins, 2003).

Performances of three groups were compared to determine the parameters' consistency. The following variables were compared: stroke length, normalized stroke length, duration of stroke phases and their ratio, peak handle pull force, peak foot reaction force, average handle pull force during drive phase, average foot reaction force during drive phase, and force ratios and the instant of occurrence, stroke work, handle motion trajectories, trunk inclination and joint torques.

The stroke length (l) was defined as the difference between the maximum and minimum length of the handle displacement. Normalized stroke length (l_r) was calculated as the average stroke length divided by the height of the rower. The ratio of the stroke phases (r) was represented as the ratio between the duration of the drive phase (t_d) and the recovery phase (t_r), where the backward motion of the handle, away from the flywheel, represented the drive phase, while the recovery phase was determined as the handle motion in the opposite direction. The peak handle pull force ($f_{p,max}$) represented the maximum value of force measured on the handle during a single stroke. The average handle pull force during the drive ($f_{p,avg}$) was the average of force measured on the handle during a drive phase of the stroke. The ratio average to maximal handle pull force ($f_{p,r}$) was calculated as the ratio between $f_{p,avg}$ and $f_{p,max}$. The peak foot reaction force ($f_{r,max}$) was the maximum absolute value of the measured force vector on the foot stretcher during a single stroke. The average foot reaction force during the drive ($f_{r,avg}$) was the average absolute value of the measured force vector on the foot stretcher during a drive phase of the stroke. The ratio average to maximal foot reaction force ($f_{r,r}$) was calculated as the ratio between $f_{r,avg}$ and $f_{r,max}$. Ratio of peak forces as a parameter describing rowing style ($f_{r,m}$) was determined as ratio between $f_{p,max}$ and $f_{r,max}$, while ratio of average forces during the drive ($f_{r,a}$) was determined as ratio between $f_{p,avg}$ and $f_{r,avg}$. The work of a stroke (A) was calculated as the integral of handle pull force over handle displacement. Trunk inclination (φ) was defined as the angle between trunk described by a vector from marker M10 to marker M11 and coronal plane. The handle motion trajectory was assessed directly from the measured position of marker attached to the handle. The torque around the transversal direction (M_z) was analyzed as the most important parameter of joint loadings that contribute to movement in the sagittal plane. To enable better comparison, data have been normalized to a longitudinal handle displacement. The beginning of the drive was assigned to a value of −100, the end of the pull and the start of the recovery to value 0 and the end of the recovery to a value of 100. From torque parameter of maximal torque around the transversal direction (M_z) and their instant of occurrence according to handle position (M_h) were calculated.

2.5. Data processing and statistical analyses

Data from ten consecutive strokes accomplished at each stroke rate from each participant were acquired for analysis. The Matlab software package (The MathWorks (Ver. 7.10), Natict, MA) was used for data processing. The start of a rowing stroke was defined as the start of the drive phase; therefore, the recovery phase covers the second half of the total rowing stroke.

Evaluation of motion performance was assessed by calculating the trajectory repeatability (RT_p) following the ISO 9283 standard (1998), which is used for evaluation of the industrial robots. Trajectory repeatability at a single point of trajectory (RT_{pi}) is defined as the radius of a circle containing all measured paths at this point. The trajectory repeatability for the whole trajectory (RT_p) is defined as maximum value of trajectory repeatabilities (RT_{pi}).

Data from ten consecutive strokes at each stroke rate from each participant were averaged and analyzed with SPSS (IBM (Ver. 17.0), Armonk, NY). As we were interested in the analysis of the stroke rate influence to listed variables in differently skilled groups, we first performed a one-way repeated-measures ANOVA with three levels of stroke rate (20 str/min, 26 str/min, 34 str/min) for each variable. From this ANOVA, we extracted the partial eta-squared value (η^2) and the p-value of the effect of stroke rate on each variable for each group separately. The partial eta-squared represents the proportion of total variability attributable to the factor (in this case, stroke rate), excluding other factors from the total nonerror variation (Cohen, 1973) and can thus be thought of as the 'size' of the factor's effect. Partial eta-squared has been previously used to study the size of the effect of task difficulty and subject type on physiological and biomechanical parameters (Novak et al., 2010).

Since we were also interested in investigating the differences between the groups, we performed a two-way mixed-design ANOVA with one within-subject factor (stroke rate) and one between-subjects factor (rower type). From this ANOVA, we extracted the partial eta-squared and the p-value of the effect of rower type (elite, junior or non-rower) on each variable. In all cases, the threshold for significance was set at $p = .05$.

The variance-to-mean ratio (VMR) was used to evaluate the consistency of variables. A VMR below .05 was considered insignificant.

We performed a principal component analysis (PCA) in order to analyze variance between participating subjects. PCA was performed for the drive phase for signals of handle pull force, foot reaction force and trunk inclination as the basic parameter of body posture. For proper comparison, all stroke signals were resampled to the same number of samples and forces were normalized with maximal force. The principal components (i.e., eigenvectors) were found by the eigenvalue decomposition of the covariance matrix of all signals coming from all measured data from the elite rowers. After that, all signals were projected to the PCA subspace. For better comparison, the eigenvectors were scaled by the inverse of the square root of the corresponding eigenvalues.

3. Results and discussion

Means and standard deviations of the stroke length (l), normalized stroke length (l_n), duration of drive phase (t_d), duration of recovery phase (t_r), ratio of the stroke phases (r), peak foot reaction force ($f_{r,max}$), average foot reaction force during the drive ($f_{r,avg}$), ratio average to maximal foot reaction force ($f_{r,r}$), peak handle pull force ($f_{p,max}$), average handle pull force during the drive ($f_{p,avg}$), ratio average to maximal handle pull force ($f_{p,r}$), force ratio of peak forces ($f_{r,m}$), force ratio of average forces during the drive ($f_{r,a}$), work (A) and repeatability for the handle motion trajectory (RT_p) are shown in Table 1 for elite rowers, in Table 2 for junior rowers, and in Table 3 for non-rowers. For each group of rowers also group averages and standard deviations are presented.

Table 1
Means and standard deviations of movement kinematics and kinetics of elite rowers.

Subject	Rate [st/min]	l [m]	l_n	t_d [s]	t_r [s]	r	$f_{r.max}$ [N]	$f_{r.avg}$ [N]	$f_{r,r}$	$f_{p.max}$ [N]	$f_{p.avg}$ [N]	$f_{p,r}$	$f_{r,m}$	$f_{r,a}$	A [J]	RT_p [m]
E1	20	1.611 (0.015)	0.848	0.91 (0.01)	2.07 (0.03)	1:2.25	1337 (40)	744 (20)	0.56	1123 (35)	497 (18)	0.44	0.84	0.67	929 (37)	0.025
	26	1.631 (0.011)	0.858	0.85 (0.02)	1.48 (0.02)	1:1.74	1347 (16)	771 (15)	0.57	1165 (16)	508 (13)	0.44	0.86	0.66	962 (21)	0.025
	34	1.632 (0.006)	0.859	0.79 (0.01)	1.11 (0.02)	1:1.41	1339 (18)	783 (8)	0.58	1153 (13)	513 (11)	0.44	0.86	0.65	982 (17)	0.026
E2	20	1.606 (0.003)	0.820	0.93 (0.02)	1.88 (0.11)	1:2.02	1189 (22)	638 (12)	0.54	1091 (46)	467 (26)	0.43	0.92	0.73	883 (37)	0.039
	26	1.631 (0.001)	0.832	0.85 (0.02)	1.35 (0.07)	1:1.58	1195 (20)	663 (17)	0.55	1167 (26)	485 (14)	0.42	0.98	0.73	950 (23)	0.044
	34	1.603 (0.014)	0.818	0.72 (0.01)	0.87 (0.02)	1:1.20	1235 (12)	742 (8)	0.60	1204 (13)	536 (8)	0.45	0.97	0.72	1030 (17)	0.038
E3	20	1.603 (0.001)	0.814	0.98 (0.01)	1.94 (0.05)	1:1.97	1365 (42)	671 (14)	0.49	974 (27)	443 (16)	0.45	0.71	0.66	839 (29)	0.042
	26	1.615 (0.002)	0.820	0.92 (0.02)	1.50 (0.03)	1:1.63	1348 (49)	662 (27)	0.49	1031 (48)	455 (25)	0.44	0.77	0.69	897 (50)	0.042
	34	1.600 (0.010)	0.812	0.73 (0.01)	0.95 (0.03)	1:1.29	1432 (39)	825 (14)	0.58	1303 (17)	597 (11)	0.46	0.91	0.73	1153 (21)	0.044
E4	20	1.638 (0.023)	0.866	0.99 (0.01)	1.83 (0.07)	1:1.85	1123 (42)	635 (17)	0.57	960 (38)	390 (14)	0.41	0.85	0.61	786 (31)	0.058
	26	1.667 (0.010)	0.882	0.91 (0.02)	1.50 (0.04)	1:1.64	1187 (17)	675 (20)	0.57	1041 (29)	422 (14)	0.41	0.88	0.62	864 (27)	0.065
	34	1.642 (0.007)	0.869	0.80 (0.01)	1.00 (0.02)	1:1.25	1194 (17)	713 (18)	0.60	1057 (16)	488 (11)	0.46	0.89	0.63	908 (26)	0.026
E5	20	1.509 (0.001)	0.812	0.92 (0.01)	1.93 (0.06)	1:2.09	1182 (43)	668 (17)	0.57	986 (38)	423 (15)	0.43	0.83	0.63	799 (21)	0.025
	26	1.486 (0.012)	0.799	0.85 (0.02)	1.47 (0.06)	1:1.71	1226 (46)	674 (24)	0.55	1062 (28)	444 (27)	0.42	0.87	0.66	847 (35)	0.049
	34	1.457 (0.024)	0.784	0.78 (0.02)	1.08 (0.04)	1:1.40	1297 (32)	706 (17)	0.54	1105 (13)	461 (9)	0.42	0.85	0.65	870 (15)	0.056
Group average	20	1.593 (0.049)	0.832 (0.024)	0.95 (0.04)	1.93 (0.09)	1:2.04 (0.16)	1239 (106)	671 (44)	0.54 (0.03)	1027 (75)	444 (41)	0.43 (0.02)	0.83 (0.08)	0.66 (0.05)	847 (59)	0.038 (0.014)
	26	1.606 (0.070)	0.838 (0.032)	0.88 (0.04)	1.46 (0.06)	1:1.67 (0.07)	1261 (81)	689 (46)	0.55 (0.03)	1093 (67)	463 (34)	0.42 (0.01)	0.87 (0.07)	0.67 (0.04)	904 (51)	0.045 (0.014)
	34	1.587 (0.075)	0.828 (0.035)	0.76 (0.04)	1.00 (0.10)	1:1.31 (0.08)	1299 (93)	754 (50)	0.58 (0.02)	1164 (95)	519 (52)	0.45 (0.02)	0.90 (0.05)	0.68 (0.05)	989 (111)	0.038 (0.013)

NOTE: The stroke length (l), normalized stroke length (l_n), duration of drive phase (t_d), duration of recovery phase (t_r), ratio of the stroke phases (r), peak foot reaction force ($f_{r,max}$), average foot reaction force during the drive ($f_{r,avg}$), ratio average to maximal foot reaction force ($f_{r,r}$), peak handle pull force ($f_{p,max}$), average handle pull force during the drive ($f_{p,avg}$), ratio average to maximal handle pull force ($f_{p,r}$), force ratio of peak forces ($f_{r,m}$), force ratio of average forces during the drive ($f_{r,a}$), work (A) and repeatability for the handle motion trajectory (RT_p).

Table 2
Means and standard deviations of movement kinematics and kinetics of junior rowers.

	Rate [st/min]	l [m]	l_n	t_d [s]	t_r [s]	r	$f_{r.max}$ [N]	$f_{r.avg}$ [N]	$f_{r,r}$	$f_{p.max}$ [N]	$f_{p.avg}$ [N]	$f_{p,r}$	$f_{r,m}$	$f_{r,a}$	A [J]	RT_p [m]
J1	20	1.579 (0.012)	0.86	1.00 (0.03)	1.97 (0.06)	1:1.98	1195 (93)	641 (18)	0.54	879 (66)	394 (12)	0.45	0.74	0.61	733 (59)	0.040
	26	1.596 (0.012)	0.89	0.92 (0.01)	1.42 (0.03)	1:1.54	1224 (43)	649 (9)	0.53	931 (20)	401 (9)	0.43	0.76	0.62	762 (19)	0.028
	34	1.541 (0.009)	0.86	0.82 (0.01)	0.97 (0.03)	1:1.18	1175 (30)	646 (22)	0.55	971 (38)	401 (17)	0.41	0.82	0.62	734 (27)	0.040
J2	20	1.559 (0.013)	0.83	1.05 (0.03)	1.88 (0.06)	1:1.78	855 (75)	563 (20)	0.66	820 (37)	369 (22)	0.45	0.96	0.66	706 (41)	0.050
	26	1.566 (0.018)	0.83	0.96 (0.01)	1.27 (0.03)	1:1.32	866 (40)	557 (14)	0.64	858 (23)	375 (10)	0.44	0.99	0.67	724 (23)	0.041
	34	1.527 (0.015)	0.82	0.84 (0.01)	0.92 (0.04)	1:1.10	1015 (36)	644 (24)	0.63	940 (52)	435 (30)	0.46	0.93	0.67	820 (63)	0.037
J3	20	1.699 (0.019)	0.90	1.20 (0.02)	1.69 (0.07)	1:1.41	912 (37)	445 (18)	0.49	760 (42)	288 (15)	0.38	0.83	0.65	604 (35)	0.027
	26	1.708 (0.007)	0.91	1.04 (0.01)	1.30 (0.04)	1:1.26	989 (33)	502 (15)	0.51	898 (39)	338 (12)	0.38	0.91	0.67	688 (28)	0.041
	34	1.681 (0.009)	0.89	0.91 (0.01)	0.92 (0.03)	1:1.01	1009 (17)	565 (15)	0.56	976 (27)	375 (10)	0.38	0.96	0.66	759 (21)	0.037
J4	20	1.558 (0.006)	0.86	0.97 (0.02)	1.92 (0.05)	1:1.97	998 (58)	568 (23)	0.57	821 (41)	396 (20)	0.48	0.82	0.70	714 (32)	0.046
	26	1.574 (0.012)	0.87	0.89 (0.03)	1.35 (0.05)	1:1.51	1143 (55)	623 (65)	0.55	888 (67)	405 (42)	0.46	0.77	0.65	749 (73)	0.063
	34	1.566 (0.007)	0.87	0.78 (0.01)	0.93 (0.02)	1:1.19	1286 (26)	701 (16)	0.55	954 (34)	446 (24)	0.47	0.74	0.63	809 (38)	0.036
J5	20	1.578 (0.016)	0.88	0.94 (0.01)	2.05 (0.10)	1:2.19	1196 (63)	730 (18)	0.61	927 (26)	434 (16)	0.47	0.77	0.59	849 (33)	0.111
	26	1.581 (0.014)	0.89	0.85 (0.02)	1.39 (0.06)	1:1.64	1220 (59)	726 (20)	0.60	982 (28)	441 (12)	0.45	0.81	0.60	862 (23)	0.046
	34	1.560 (0.007)	0.88	0.76 (0.01)	1.00 (0.03)	1:1.31	1227 (28)	771 (10)	0.63	1021 (26)	439 (8)	0.43	0.83	0.57	829 (15)	0.166
Group average	20	1.595 (0.059)	0.87 (0.03)	1.03 (0.10)	1.90 (0.13)	1:1.84 (0.29)	1031 (158)	589 (105)	0.57 (0.07)	841 (63)	376 (54)	0.45 (0.04)	0.82 (0.08)	0.64 (0.04)	721 (87)	0.056 (0.032)
	26	1.605 (0.059)	0.88 (0.03)	0.93 (0.07)	1.35 (0.06)	1:1.44 (0.16)	1088 (156)	611 (86)	0.56 (0.05)	911 (47)	392 (38)	0.43 (0.03)	0.85 (0.10)	0,64 (0.03)	757 (65)	0.048 (0.014)
	34	1.575 (0.061)	0.86 (0.03)	0.82 (0.06)	0.95 (0.04)	1:1.15 (0.11)	1142 (125)	665 (76)	0.58 (0.04)	972 (30)	419 (30)	0.43 (0.03)	0.86 (0.09)	0.63 (0.04)	790 (41)	0.064 (0.057)

NOTE: The stroke length (l), normalized stroke length (l_n), duration of drive phase (t_d), duration of recovery phase (t_r), ratio of the stroke phases (r), peak foot reaction force ($f_{r,max}$), average foot reaction force during the drive ($f_{r,avg}$), ratio average to maximal foot reaction force ($f_{r,r}$), peak handle pull force ($f_{p,max}$), average handle pull force during the drive ($f_{p,avg}$), ratio average to maximal handle pull force ($f_{p,r}$), force ratio of peak forces ($f_{r,m}$), force ratio of average forces during the drive ($f_{r,a}$), work (A) and repeatability for the handle motion trajectory (RT_p).

Table 3
Means and standard deviations of movement kinematics and kinetics of non-rowers.

Subject	Rate [st/min]	l [m]	l_r	t_d [s]	t_r [s]	r	$f_{r.max}$ [N]	$f_{r.avg}$ [N]	$f_{r,r}$	$f_{p.max}$ [N]	$f_{p.avg}$ [N]	$f_{p,r}$	$f_{r,m}$	$f_{r,a}$	A [J]	RT_p [m]
N1	20	0.859 (0.025)	0.462	1.48 (0.03)	1.48 (0.02)	1:1.00	354 (21)	191 (11)	0.54	71 (16)	26 (5)	0.37	0.20	0.14	48 (6)	0.063
	26	0.932 (0.027)	0.501	1.17 (0.03)	1.18 (0.05)	1:1.01	592 (28)	248 (23)	0.42	163 (47)	50 (19)	0.31	0.27	0.20	94 (23)	0.093
	34	0.914 (0.026)	0.492	0.87 (0.02)	0.96 (0.03)	1:1.10	832 (38)	394 (34)	0.47	332 (69)	93 (24)	0.28	0.40	0.24	165 (27)	0.074
N2	20	1.129 (0.016)	0.661	1.12 (0.03)	1.42 (0.15)	1:1.27	600 (100)	371 (30)	0.62	465 (80)	141 (21)	0.30	0.78	0.38	213 (30)	0.075
	26	1.240 (0.050)	0.725	1.11 (0.02)	1.29 (0.05)	1:1.16	752 (99)	439 (31)	0.58	528 (79)	166 (27)	0.31	0.70	0.38	278 (53)	0.062
	34	1.352 (0.023)	0.791	0.89 (0.03)	0.94 (0.02)	1:1.06	924 (64)	548 (21)	0.59	703 (59)	243 (20)	0.35	0.76	0.44	432 (32)	0.070
N3	20	1.171 (0.037)	0.640	1.55 (0.05)	1.20 (0.07)	1:0.77	511 (34)	210 (14)	0.41	91 (25)	33 (10)	0.36	0.18	0.16	93 (11)	0.090
	26	1.151 (0.022)	0.629	1.23 (0.03)	0.99 (0.05)	1:0.81	531 (42)	254 (16)	0.48	140 (30)	51 (12)	0.36	0.26	0.20	133 (15)	0.062
	34	1.241 (0.029)	0.678	0.92 (0.02)	0.88 (0.03)	1:0.95	813 (23)	415 (22)	0.51	353 (46)	137 (16)	0.39	0.43	0.33	293 (30)	0.049
N4	20	0.827 (0.048)	0.445	1.52 (0.07)	1.44 (0.32)	1:0.94	363 (26)	200 (7)	0.55	69 (17)	27 (8)	0.39	0.19	0.14	49 (8)	0.034
	26	1.099 (0.033)	0.591	1.11 (0.04)	1.14 (0.17)	1:1.02	723 (62)	326 (30)	0.45	221 (33)	77 (15)	0.35	0.31	0.24	166 (26)	0.046
	34	1.278 (0.029)	0.687	0.87 (0.01)	0.95 (0.02)	1:1.09	970 (80)	568 (39)	0.59	627 (47)	233 (19)	0.37	0.65	0.41	468 (30)	0.071
N5	20	0.893 (0.033)	0.475	1.39 (0.05)	1.50 (0.06)	1:1.08	485 (14)	267 (20)	0.55	101 (26)	39 (10)	0.39	0.21	0.15	61 (12)	0.086
	26	1.018 (0.056)	0.542	1.15 (0.05)	1.16 (0.04)	1:1.01	585 (12)	298 (20)	0.51	178 (34)	66 (11)	0.37	0.31	0.22	124 (17)	0.108
	34	1.019 (0.024)	0.542	0.91 (0.02)	0.94 (0.06)	1:1.02	735 (31)	364 (40)	0.50	280 (54)	101 (27)	0.36	0.38	0.28	186 (35)	0.084
Group average	20	0.976 (0.161)	0.537 (0.105)	1.41 (0.17)	1.41 (0.12)	1:1.00 (0.18)	463 (104)	248 (75)	0.53 (0.08)	159 (171)	53 (49)	0.36 (0.04)	0.31 (0.26)	0.19 (0.11)	93 (70)	0.070 (0.023)
	26	1.088 (0.119)	0.598 (0.086)	1.15 (0.05)	1.15 (0.11)	1:1.00 (0.13)	637 (96)	313 (77)	0.49 (0.06)	246 (160)	82 (48)	0.34 (0.03)	0.37 (0.19)	0.25 (0.07)	159 (71)	0.074 (0.025)
	34	1.161 (0.186)	0.638 (0.120)	0.89 (0.02)	0.93 (0.03)	1:1.05 (0.06)	855 (93)	458 (94)	0.53 (0.05)	459 (192)	161 (72)	0.35 (0.04)	0.52 (0.17)	0.34 (0.09)	309 (138)	0.070 (0.013)

NOTE: The stroke length (l), normalized stroke length (l_n), duration of drive phase (t_d), duration of recovery phase (t_r), ratio of the stroke phases (r), peak foot reaction force ($f_{r,max}$), average foot reaction force during the drive ($f_{r,avg}$), ratio average to maximal foot reaction force ($f_{r,r}$), peak handle pull force ($f_{p,max}$), average handle pull force during the drive ($f_{p,avg}$), ratio average to maximal handle pull force ($f_{p,r}$), force ratio of peak forces ($f_{r,m}$), force ratio of average forces during the drive ($f_{r,a}$), work (A) and repeatability for the handle motion trajectory (RT_p).

Table 4
Partial eta-squared obtained using analysis of variance for different parameters.

	L_n	r	A	RT_p	φ_s	φ_f	M_{z_k}	M_{h_k}	M_{z_ls}	M_{h_ls}
Elite	0.33	0.99*	0.65*	0.53	0.58	0.69*	0.36	0.77*	0.57	0.04
Junior	0.70*	0.94*	0.44	0.11	0.07	0.03	0.14	0.23	0.53	0.78*
Non-rower	0.60*	0.08	0.79*	0.03	0.14	0.10	0.84*	0.03	0.75*	0.72*
Type E-N	0.78*	0.92*	0.97*	0.57*	0.70*	0.37	0.70*	0.01	0.93*	0.47*
Type E-J	0.34	0.31	0.68*	0.07	0.05	0.20	0.07*	0.00	0.78*	0.16
Type E-J-N	0.84*	0.83*	0.96*	0.29	0.53*	0.48*	0.70*	0.01	0.91*	0.35

	$f_{r,max}$	$f_{r,avg}$	$f_{r,r}$	$f_{p,max}$	$f_{p,avg}$	$f_{p,r}$	$f_{r,m}$	$f_{r,a}$
Elite	0.62*	0.69*	0.52	0.58	0.60	0.56	0.43	0.20
Junior	0.45	0.69*	0.24	0.86*	0.60	0.33	0.15	0.11
Non-rower	0.87*	0.85*	0.27	0.83*	0.80*	0.16	0.66*	0.79*
Type E-N	0.95*	0.93*	0.23	0.93*	0.95*	0.80*	0.76*	0.93*
Type E-J	0.42*	0.32	0.04	0.80*	0.55*	0.01	0.03	0.17
Type E-J-N	0.89*	0.87*	0.24	0.93*	0.95*	0.72*	0.78*	0.93*

NOTE: The first row represents the effect of stroke rate on various variables for elite rowers, the second row represents the effect of stroke rate on various variables for junior rowers, and the third row represents the effect of stroke rate on various variables for non-rowers. The fourth, fifth, and sixth rows describe the impact of rower type on listed variables. Asterisk represents significant effect with $p < .05$.

Results for one-way repeated-measures ANOVA with three levels of stroke rate and two-way mixed-design ANOVA with one within-subject factor (stroke rate) and one between-subjects factor (rower type) are presented in Table 4. A two-way mixed-design ANOVA was performed separately for rower types elites and non-rowers (Rower type E-N), elites and junior rowers (Rower type E-J), and elites, junior rowers, and non-rowers (Rower type E-J-N). The first three rows describe the influence of the stroke rate on the listed variables. An asterisk means that there is at least a 95% confidence that the differences in variables are not random, but are a consequence of the changes in stroke rate. The numbers represent the size of the effect of the stroke rate, where $\eta^2 > .7$ presents major stroke rate effect. The fourth, fifth, and sixth rows describe the impact of rower type on listed variables. An asterisk means that there is at least a 95% confidence that differences in variables are not random, but are a consequence of rower type. This means that the variable can be used for identification between rower types and characterizes the distinction in ergometer rowing technique. A higher number describes greater distinction.

3.1. Stroke length

As can be seen from the Table 1, the pattern of stroke length in elite rowers is extremely consistent through different stroke rates, with an average standard deviation (*SD*) of less than 1 cm. Only in subject E5 the stroke length shortens with increasing stroke rate. Normalized stroke length is used for intercomparison of subjects. The average normalized stroke length of elite rowers at all stroke rates is 0.83 (*SD* = .03). Value *VMR* = .04 is considered insignificant. The stroke length of junior rowers varies with stroke rate (see Table 2). All subjects lengthen stroke length at stroke rate 26 str/min and shorten it at stroke rate 34 str/min. All subjects, except J4, row with the shortest stroke length at stroke rate 34 str/min. The average normalized stroke length of junior rowers is 0.87 (*SD* = .03) and longer then elites'. Value *VMR* = .03 is considered insignificant. The stroke length of non-rowers varies even more considerably (see Table 3). The normalized stroke length is smaller than that of elite and junior rowers and increases with increasing stroke rate (0.54 (*SD* = .10) at 20 str/min, 0.60 (SD = .09) at 26 str/min, 0.64 (*SD* = .12) at 34 str/min). Video analysis has shown that the shorter stroke length is a consequence of smaller trunk inclination and knee flexion at the beginning of the drive, and shortening the stroke at the finish of the drive phase, as non-rowers do not pull the handle to the abdomen due to their lack of technique knowledge. The average SD of strokes at the same rate is less than 3 cm, meaning that non-rowers row with a fairly constant stroke length at a certain stroke rate. On this basis we can conclude that the stroke length of elite rowers is consistent and not dependent on the stroke rate ($p = .21$) while the stroke length of junior rowers and non-rowers is consistent only within the same stroke rate. Junior rowers first lengthen and then shorten stroke length with increasing stroke rate ($p = .03$), and non-rowers lengthens it with increasing stroke rate ($p = .04$).

3.2. Duration of stroke phases

The results from Tables 1 and 2 show that the elite and junior rowers perform a fast drive and a slow recovery during a single stroke, so the ratio between the drive and recovery phase durations decreases with increasing stroke rate ($p < .01$). This means that the recovery duration has more influence on the stroke rate than drive duration. The ratio of junior rowers is on average 10% lower than in elites'. This is correlated with applied forces; stronger rowers spend less time in the drive phase. Non-rowers achieve a lower ratio (around 1:1), which does not change significantly ($p = .60$) with increasing stroke rate (see Table 4). This means that they spend equal time for both phases. We can conclude that the ratio of stroke phases of elite and junior rowers is constant at the same stroke rate but dependent on the stroke rate.

3.3. Forces

From the Table 1 it is evident that the value of peak foot reaction force $f_{r,max}$ of elite rowers lies between 1123 and 1432 N and the value of average foot reaction force during the drive phase $f_{r,avg}$ between 635 and 825 N. The results show that the average $f_{r,max}$ at stroke rate 34 str/min is 4.7% higher than that at stroke rate 20 str/min, while average $f_{r,avg}$ is 12.4% higher. It is a small increase, but can be noticed as a trend ($f_{r,max}$: $p = .02$, $f_{r,avg}$: $p = .03$). The value of the force ratio $f_{r,r}$ varies between subjects from 0.49 (E3 at 20 and 26 str/min) to 0.60 (E2 and E4 at 30 str/min); however it increases with stroke rate at all elite subjects, with the exception of subject E5. The results show that the average VMR of $f_{r,avg}$ and $f_{r,max}$ within the same stroke rate is 0.02 and can be considered insignificant.

The value of the peak handle pull force $f_{p,max}$ of elite rowers is between 960 and 1107 N and the value of average handle pull force during the drive phase $f_{p,avg}$ is between 390 and 597 N. It can be seen from the results that the average $f_{p,max}$ at stroke rate 34 str/min is 11.8% higher than that at stroke rate 20 str/min, while average $f_{p,avg}$ is 16.9% higher. The trend of increasing $f_{p,max}$ and $f_{p,avg}$ with increasing stroke rate is evident in all elite rowers ($f_{r,max}$: $p = .07$, $f_{r,avg}$: $p = .06$). The value of the force ratio $f_{p,r}$ varies between subjects from 0.41 (E4 at 20 and 26 str/min) to 0.46 (E3 and E4 at 34 str/min); however it remains the same at subject E1. Subjects E2, E3 and E5 perform with lower ratio at stroke rate 26 str/min than at stroke rate 20 str/min; subjects E2, E3 and E4 increase the ratio at stroke rate 34 str/min. The results show that the average VMR of $f_{p,avg}$ and $f_{p,max}$ within the same stroke rate is 0.03 and can be considered insignificant.

The force ratio of peak forces $f_{r,m}$ and force ratio of average forces during the drive phase $f_{r,a}$ vary between elite rowers. The $f_{r,m}$ of subject E1 stays constant at different stroke rates, it changes significantly in subject E3. The $f_{r,a}$ of subjects E1 and E2 decrease with increasing stroke rate, while the $f_{r,a}$ of other elite subjects increase. This indicates slight differences in technique amongst elite rowers and could be the subject of further research.

Regarding Table 2, the value of peak foot reaction force $f_{r,max}$ of junior rowers lies between 855 and 1286 N and are on average 14.2% smaller than elites'. It can be seen from the results that the average $f_{r,max}$ at stroke rate 26 str/min is 5.5% and at stroke rate 34 str/min 10.8% higher than that at stroke rate 20 str/min. Trend of higher $f_{r,max}$ is present in all the junior rowers, except J1, who has achieved the lowest $f_{r,max}$ at stroke rate 34 str/min. The value of average foot reaction force during the drive phase $f_{r,avg}$ of juniors lies between 445 and 771 N and are on average 11.8% smaller than elites'. The $f_{r,avg}$ increases with stroke rate at subjects J2, J3, and J4, while varies at J1 and J5. The results show that the average VMR of $f_{r,max}$ within the same stroke rate is 0.04 and 0.03 of $f_{r,avg}$, what can be considered insignificant. The value of the force ratio $f_{r,r}$ varies between subjects from 0.49 (J3 at 20 str/min) to 0.66 (J2 at 20 str/min); however there is no noticeable distinction from elite rowers in these values.

The value of the peak handle pull force $f_{p,max}$ of junior rowers lies between 760 and 1021 N and are on average 17.1% smaller than elites'. It can be seen from the results that the average $f_{p,max}$ at stroke

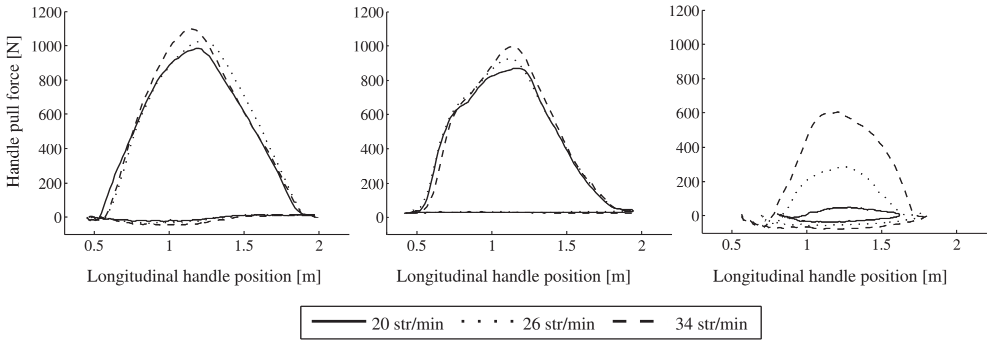

Fig. 2. Handle pull force during a single stroke at different stroke rates: elite rower E5 (left), junior rower J1 (central) and non-rower N4 (right).

rate 26 str/min is 8.3% and at stroke rate 34 str/min is 15.86% higher than that at stroke rate 20 str/min. This trend of increasing $f_{p,max}$ with increasing stroke rate is evident in all the junior rowers ($p < .01$). The value of average handle pull force during the drive phase $f_{p,avg}$ of juniors lies between 288 and 446 N and are on average 16.6% smaller than elites'. The $f_{p,avg}$ increases with stroke rate at all junior subjects, except J5 ($p = .07$). The results show that the average VMR of $f_{p,max}$ and $f_{p,avg}$ within the same stroke rate are 0.04 and can be considered insignificant. The value of the force ratio $f_{p,r}$ varies between subjects from 0.38 (J3 at all stroke rates) to 0.47 (J4 at 34 str/min, J5 at 20 str/min); however there is no noticeable distinction from elite rowers in these values.

The force ratio of peak forces $f_{r,m}$ and force ratio of average forces during the drive phase $f_{r,a}$ vary between junior rowers inconsistently. While the $f_{r,m}$ of subjects J1, J3 and J5 increase with stroke rate, it lowers in subject J4. The $f_{r,a}$ of subjects J1, J2 and J3 stays constant at different stroke rates, but changes significantly in subject J4.

The forces produced by non-rowers are significantly lower than the forces of the elite and junior rowers. The most obvious difference occurs at a rate of 20 str/min, where non-rowers (except subject N2) hardly produce any force on the handle. The $f_{p,max}$, $f_{r,max}$, $f_{p,avg}$, and $f_{r,avg}$ increase considerably with increasing stroke rate. The $f_{r,max}$ of subject N4 increases by 2.6 times and $f_{p,max}$ tenfold. The $f_{r,avg}$ increase on average for 26% at stroke rate 26 str/min and 85% at stroke rate 34 str/min, while $f_{p,avg}$ almost double at 26 str/min and triple at 34 str/min. At the stroke rate of 34 str/min, non-rowers develop around 2/3 of the elite rowers' foot reaction forces, but they are obviously not able to transfer this force to the handle, where their force is only around 1/3 of the elites'. Exceptions are evident in subjects N2 and N4, who could develop around 1/2 $f_{p,max}$ of elite rowers. The force ratios of non-rowers vary and are lower than elites', with the exception of the $f_{r,r}$, which do not differentiate from the elite and junior rowers.

Fig. 2 shows the dependency of handle pull force on longitudinal handle position of a single stroke at different stroke rates. The results are presented for one typical rower from each group. Typical handle pull force rapidly increases during the drive, reaches its maximum value, and then declines over time. The forces during the recovery phase are minimal. The handle pull force trajectories in the left part of Fig. 2 show how subject E5 increases the force peak, while the force profiles remain similar. There is less time for each stroke at a higher stroke rate, so the force profile is completed faster. This finding is not consistent with the findings of McGregor et al. (2004), who observed a trend of reduction of the peak pulling force and changes in shape of the force curves during increasing stroke rate. The force trajectories presented in central part of Fig. 2 show how subject J1 increases the force peak and changes the force profile with increasing stroke rate. The force profile from junior rower J1 also differs from force profile of elite rower E5. The force trajectories presented in right part of Fig. 2 show how non-rower N4 changes the force profile with increasing stroke rate.

On the basis of force analysis we can conclude that the peaks of the handle pull forces of elite and junior rowers are constant at the same stroke rate, but increase slightly with increasing stroke rate.

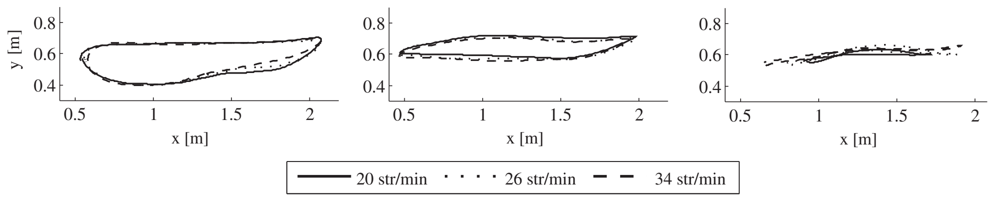

Fig. 3. Handle motion trajectories during a single stroke at different stroke rates: elite rower E5 (left), junior rower J1 (central) and non-rower N4 (right).

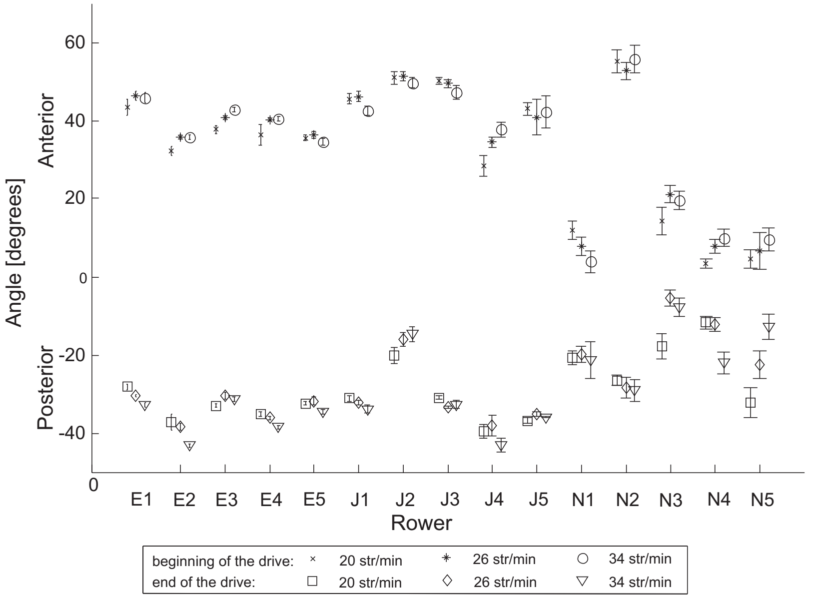

Fig. 4. Trunk inclination at the instant of start and finish of drive phase.

The force ratio depends on the technique of the rower. It is also evident that elite rowers do not change their force profile regarding the handle position, while junior rowers change it. The peak forces of junior rowers are smaller than the peak forces of elite rowers, and the peak forces of non-rowers are significantly smaller than the peak forces of junior rowers and increase significantly ($p < .01$) with increasing stroke rate.

3.4. Work

The work performed during a single stroke is smaller for junior rowers than for elite rowers, and much smaller for non-rowers than for junior rowers. Work increases with increase of the stroke rate from 20 to 34 str/min in all subjects elite rowers and non-rowers ($p < .05$). In junior rowers work decreased in subjects J1 and J5 at stroke rate 34 str/min regarding the stroke rate 26 str/min. The increase of work at stroke rate 34 str/min regarding work at stroke rate 20 str/min was assessed as 5% for subject E1, 9% for subject E4, 13% for subject J4, about 16% for subjects E2 and E4 and J2, 25% for subject J3, 37% for subject E3, while there was no increase for subject J1 and 2% decrease for subject J5. If we consider the relative increase of work, it can be seen from Tables 1 and 3 that it is much higher in non-rowers. For example, subject N2 did twice as much work at the stroke rate of 34 str/min than at the stroke rate of 20 str/min, subjects N1, N3 and N5 did about three times more work, and subject N4 did more than nine times more work. Changing the stroke rate shows a difference in work with increased stroke rate, work stays consistent in all rowers at the same stroke rate. The VMR of elite rowers is around $VMR = .03$, and of junior rowers around $VMR = .05$, and can be considered insignificant. The VMR is higher in non-rowers, on average $VMR = .14$. We conclude that work stays constant within the same stroke rate, and increases at elite and non-rowers with increased stroke rate, while at junior rowers has different patterns.

3.5. Handle motion

Fig. 3 shows the handle motion trajectories presented in the sagittal plane (x represents the horizontal direction, y represents the vertical) for the same stroke examples presented in Fig. 2. The handle of elite rower follows the upper part of motion trajectory towards the backward position (increasing x). During the recovery phase, the handle of elite rowers then decrease x by following the lower part of the trajectory in Fig. 3 until the start of the next stroke. As can be observed from Fig. 3 and statistical results from Table 4, there are no variations observed in the handle motion of the elites ($p = .73$), junior rowers ($p = .53$) at various stroke rates and between these two groups ($p = .44$). The transition of the handle motion to the recovery phase starts with an abrupt push downward, simulating the lifting of the oars from the water, followed by a horizontal return to the initial position as preparation for the new stroke. The handle motion trajectories of the non-rowers are more variable at different strokes; there is no circular motion which is typical of elite rowers. Fig. 3 also evidently shows the shorter stroke length of non-rowers. The calculated parameter RT_p in (Tables 1–3) presents quantitative assessment of handle motion repeatability. It can be seen from the results that handle motion repeatability of elite and junior rowers is similar, while in non-rowers the handle trajectories are dispersed twice as much. We can conclude that there are no variations in the handle motion of the elite and junior rowers at various stroke rates, while the handle motion trajectories of non-rowers demonstrate their lack of technique.

3.6. Trunk inclination

Trunk inclination is the most important parameter of body posture during the stroke (Lamb, 1989; Nolte, 2005). We examined the angle of trunk inclination at the beginning and end of the drive phase. Fig. 4 shows the angle of trunk inclination for all analyzed strokes at the instant of the beginning and

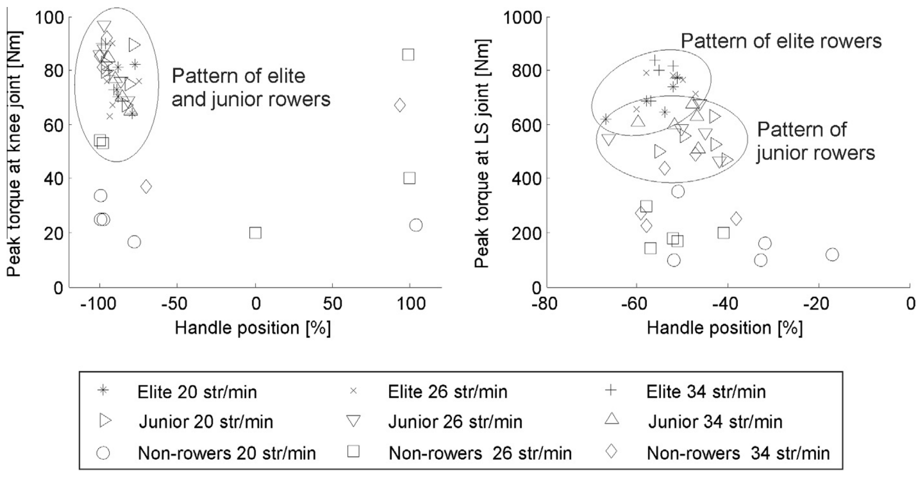

Fig. 5. The instant of peak torque at knee joint (left) and the instant of peak torque at LS joint (right) regarding handle position.

end of the drive phase for elite, junior, and non-rowers. The averaged measured values are represented by symbols together with standard deviation bar. As can be seen, the average trunk inclination angle of elite rowers is $-34.29°$ ($SD = 3.90°$) at the start of the drive and $38.93°$ ($SD = 4.27°$) at the end. Junior rowers have similar trunk inclination as elite rowers, with the exception of subject J2, who leans less forward at the beginning of drive phase, and subject J4, who leans less backward at the end of the drive phase. The average trunk inclination angle of junior rowers is $-31.60°$ ($SD = 8.31°$) at the start of the drive and $43.96°$ ($SD = 6.62°$) at the end. Non-rowers lean significantly less than elite rowers. Comparable to elites, only subject N2 leans backwards more at the end of the drive. The average trunk inclination angle of non-rowers is $-19.37°$ ($SD = 8.15°$) at the start of drive and $18.90°$ ($SD = 18.73°$) at the end of the drive. There is no evident difference regarding stroke rates ($p > .05$), except in the angle at the end of the drive phase of elite rowers ($p = .02$); however, we cannot observe any pattern in stroke dependency. We can conclude that the trunk inclination angle at the beginning and end of the drive phase of elite, junior and non-rowers stays constant with changing stroke rate. Elite and junior rowers have similar range of trunk motion, while non-rowers demonstrate smaller motion range.

3.7. Body joint loadings

From Newton-Euler inverse dynamics analysis results we investigated the loadings in knee and lumbosacral (LS) joints in detail. The knee joint transmits the foot reaction force along the lower extremities of the body while the LS joint is where lower back pain and injuries occur most frequently. Fig. 5 shows the maximal values of torque in the knee joint (left) and LS joint (right) against its occurrence depending on handle position and stroke rate for all participating subjects.

Since the elite and junior rowers produce a larger force, their joint loadings are higher than those of non-rowers, as shown in Fig. 5. It is evident that all elite and junior rowers have a similar pattern of the instant of peak value occurrence, concentrated around -89% ($SD = 7\%$ for elite rowers, $SD = 8\%$ for junior rowers) of handle position during a single stroke. Occurrences of peak values of non-rowers are scattered. The average value of peak torque at the knee joint of elite rowers is 74 Nm ($SD = 8$ Nm) at 20 str/min, 74 Nm ($SD = 10$ Nm) at 26 str/min and 82 Nm ($SD = 8$ Nm) at 34 str/min. The average value of peak torque at the knee joint of junior rowers is 79 Nm ($SD = 8$ Nm) at 20 str/min, 83 Nm ($SD = 11$ Nm) at 26 str/min and 81 Nm ($SD = 17$ Nm) at 34 str/min. The average value of peak torque at the knee joint of non-rowers increases from 25 Nm ($SD = 6$ Nm) at 20 str/min, over 51 Nm ($SD = 24$ Nm) at 26 str/min, to 72 Nm ($SD = 22$ Nm) at 34 str/min.

Since the elite and junior rowers produce a larger force, their LS joint loadings are larger than those of non-rowers. Fig. 5 shows that all the elite rowers have a similar pattern regarding the instant of peak torque value occurrence, concentrated around -55% ($SD = 5\%$) of handle position during a single stroke and junior rowers around -48% ($SD = 7\%$). The instants of peak value of non-rowers are more scattered, but occur all in the drive phase. The average value of peak torque at LS joint of elite rowers

Table 5
The variations of the principal components between subjects in the same group of expertise.

Group	Signal	PC1	PC2	PC3	PC4	PC5
	f_r	1.11	0.98	1.05	1.06	1.01
E	f_p	1.21	1.02	1.10	1.04	0.99
	φ	0.94	1.06	1.14	1.39	1.12
	f_r	2.39	1.43	1.43	1.50	1.94
J	f_p	3.20	2.42	2.41	2.38	2.35
	φ	2.29	1.64	1.74	1.61	1.65
	f_r	1.74	1.61	1.56	2.29	2.05
N	f_p	4.37	2.80	2.74	2.85	2.96
	φ	2.12	4.99	5.01	5.88	5.43

NOTE: Results are presented as standard deviation of groups of expertise level (E – elite rowers, J – junior rowers, N – non-rowers) including all stroke rates for the drive phase signals of handle pull force (f_p), foot reaction force (f_r), and trunk inclination (φ).

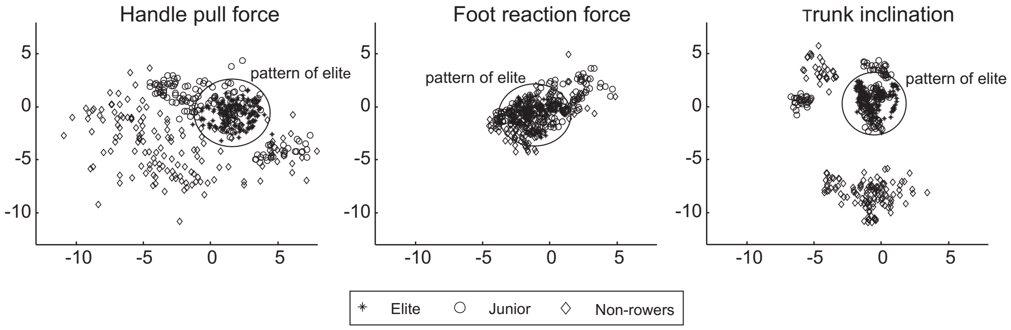

Fig. 6. Principal component analysis of the drive phase for signals of handle pull force (left), foot reaction force (central), and trunk inclination (right). The *x*-axis corresponds to the first principal component; the *y*-axis corresponds to the second principal component.

is 692 Nm (*SD* = 65 Nm) at 20 str/min, 742 Nm (*SD* = 55 Nm) at 26 str/min and 783 Nm (*SD* = 59 Nm) at 34 str/min, of junior rowers is 537 Nm (*SD* = 62 Nm) at 20 str/min, 567 Nm (*SD* = 77 Nm) at 26 str/min and 604 Nm (*SD* = 61 Nm) at 34 str/min, while in non-rowers it increases from 167 Nm (*SD* = 107 Nm) at 20 str/min, over 198 Nm (*SD* = 60 Nm) at 26 str/min, to 334 Nm (*SD* = 120 Nm) at 34 str/min. The results show that torque at the knee reaches its peak before torque at the LS joint, and that LS joint loadings are higher. We can conclude that the value of knee and LS joint loading of elite and junior rowers increases with increasing stroke rate, while the instant of peak value occurrence does not vary and has typical pattern. Loading of junior rowers are smaller than elites', and in non-rowers no typical joint loading pattern can be identified.

3.8. Principal component analysis

We compared parameter curves with a mathematical transformation in order to find the largest possible difference between them. By transformation the physical meaning is lost, only the measure of variability is shown. The first principal component is the largest possible variance between strokes, calculated using the covariance of curves, and accounts for as much of the variability in the data as possible. The first five eigen values of principal component holds more than 95% of information (handle pull force 97.11%, where each of the first five eigenvalue has a share of [59.16, 18.53, 12.04, 5.45, 1.93], feet reaction force 95.31% [41.87, 33.21, 13.75, 4.15, 2.34] and trunk inclination 99.39% [74.61, 20.56, 2.21, 1.45, 0.53]). The variations of the principal components between subjects in the same group of expertise are presented in Table 5 for handle pull force, foot reaction force and trunk inclination.

In the comparison of elite rowers, junior rowers and non-rowers we use the first two principal components as they account for 75–95% of the variability. For a targeted analysis of the individual groups of rowers, the subsequent principal components may reveal additional information on subtle differentiation in rowing techniques among individuals even though they account for a smaller percentage of variance in the data. The results of first two components of the PCA are presented in a graph in Fig. 6. The *x*-axis corresponds to the first principal component; the *y*-axis corresponds to the second principal component. From the presented results can be seen that there is no variation between elite rowers in curve shape of all three analyzed parameters. This indicates that even small group of only five elite rowers can be used for determining the values of reference parameter, and also their curves shape during the drive phase. The results of junior rowers at handle force are 2.6 times more scattered around elites' meaning, that there are variations in curves' shape and that curves' shapes differ from elites'. The 1.7 times scattering of junior rowers' results can be noticed also for foot force. Trunk inclination components of 4 junior rowers concur with pattern of the elite rowers, only one junior distinctly deviates. The principal components of handle force of non-rowers are 3.2 times more scattered as elites, while the components of foot force coincide with juniors'. The trunk inclination of non-rowers shows clusters of components, where clusters correspond to subjects. This means that non-rowers row with consistent pattern, but this pattern deviates from the pattern of elite rowers.

4. Conclusions

In the paper, biomechanical parameters were analyzed for ergometer rowing. Three groups of differently skilled rowers were compared regarding their technique and stroke rate dependency.

The results show noticeable distinctions between the elite, junior, and non-rowers. It was demonstrated that the elite rowers use a similar and consistent rowing technique at all stroke rates, technique of junior rowers use in general the similar principles, but has some deviations, while the technique of non-rowers varies. The handle motion and trunk inclination angle at the beginning of the drive phase of elite and junior rowers are constant, and are not dependent on the stroke rate. The stroke length of elite rowers is constant and not dependent on the stroke rate, while junior rowers change stroke length with stroke rate. The ratio of stroke phases, maximum forces, stroke work and joint loadings of elite and junior rowers are constant at the same stroke rate but dependent on the stroke rate.

Our analysis revealed that the technique of elite rowers is very consistent regardless of stroke rate. With the assumption that elite rowers row properly, the differences in the parameters can be used as descriptors of irregularities in ergometer rowing technique that lead to poor performance. Junior rowers differentiate from elite rowers in parameters that are linked with their strength and consecutively with intensity of rowing: peak and average foot reaction force, peak and average handle pull force, work, knee, and LS-joint torque, where values of junior rowers are lower than elites'. The juniors' handle pull force profile, which is the rowing driving force, evidently distinguish from the elites'.

The technique of non-rowers' vary significantly. The length of a stroke, the handle pull force and the foot reaction force are smaller, while the differences are evident in the handle motion trajectory and body posture during the stroke. Although the stroke length of non-rowers lengthens with increasing stroke rate, it is constant at the same stroke rate. Non-rowers do not change the ratio of stroke phases. Peak and average forces and work increase more with increasing stroke rate. Although non-rowers show lack of technique, and change it at different stroke rates, they have good consistency at the same stroke rate.

In this study, only male subjects of limited age range participated. The results acquired on this specific group and the conclusions drawn may not generalize well to both genders and all ages.

The main disadvantage of our study is considering the trunk as a single lever. Simplification imposed by a single segment trunk model causes an error in trunk inclination and LS joint loading assessment. We estimated error in LS joint loading using data from junior rowers, where position of LS joint was measured with an additional marker and trunk represented as a body with two segments. Error is estimated to be less than 3% of maximal torque value around the transversal direction. More importantly, the simplification imposed by a single segment trunk model loses information of flexion through the spine. This information is crucial for proper postural guidance and proper postural control throughout training. A new sensory system which ensures replication and is practical for utilization is in development and will be used in a training platform in the future. A wearable system of inertial measurement units that are placed at several places on the trunk will also capture information about trunk inclination and flexion throughout the spine. In this study, a single segment trunk assumption was employed only to search for patterns, and existence of differences in trunk inclination and LS joint loadings between differently skilled rowers. Another disadvantage of our study is usage of Newton-Euler inverse dynamics for calculating body joint loadings, which does not take into consideration forces on the seat. A method that would take into consideration simultaneously all contact forces would estimate the forces at the joints, especially at the LS joint, more accurately.

On the basis of the identified parameters that are stroke rate dependent (duration of stroke phases, peak and average foot reaction force, peak and average handle pull force, work, peak knee and LS joint loadings), parameters that are consistent regardless stroke rate (stroke length, handle motion, trunk inclination angle, handle pull force profile, the instant of occurrence of peak knee and LS joint loadings), and classify rowers' skill, we thus propose an ergometer rowing system which would track the identified classifying biomechanical parameters. After accomplished stroke cycle the system would calculate the stroke parameters, compare them with pre-recorded reference values of elite rowers, and advice the user for improvements. Further research will focus on investigating which types and means of feedback achieve improved technique and decreased injury on an ergometer. Presentation of virtual mirror, graphs, parameters' values, text and sound instructions, and sound effects will be considered keeping in mind the effectiveness of information transfer (Tzetzis, Mantis, Zachopoulou, & Kioumourtzoglou, 1999).

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References

Baca, A., & Kornfeind, P. (2008). A feedback system for coordination training in double rowing. *The Engineering of Sport, 7*, 659–668.
Černe, T., Kamnik, R., & Munih, M. (2011). The measurement setup for real-time biomechanical analysis of rowing on an ergometer. *Measurement, 44*, 1819–1827.
Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and Psychological Measurement, 33*, 107–112.
Consiglieri, L., & Pires, E. B. (2009). An analytical model for the ergometer rowing: Inverse multibody dynamics analysis. *Computer Methods in Biomechanical and Biomedical Engineering, 12*, 469–479.
Fothergill, S. (2010). Examining the effect of real-time visual feedback on the quality of rowing technique. *Procedia Engineering, 2*, 3083–3088.
Hahn, D., Schwirtz, A., & Huber, A. (2005). Anthropometric standardisation of multiarticular leg extension movements: A theoretical study. *Isokinetics and Exercise Science, 13*(2), 95–101.
Hase, K., Andrews, B. J., Zavatsky, A. B., & Halliday, S. E. (2002). Biomechanics of Rowing. *JJSME Internationl Journal Series C, 45*, 1082–1092.
Hase, K., Kaya, M., Zavatsky, A. B., & Halliday, S. E. (2004). Musculoskeletal loads in ergometer rowing. *Journal of Applied Biomechanics, 20*, 317–323.
Hawkins, D. (2000). A new instrumentation system for training rowers. *Journal of Biomechanics, 33*, 241–245.
Henry, J. C., Clark, R. R., McCabe, R. P., & Vanderby, R. (1995). An evaluation of instrumented tank rowing for objective assessment of rowing performance. *Journal of Sports Sciences, 13*, 199–206.
Kazunori, H., Motoshi, K., Zavatsky, A. B., & Halliday, S. E. (2004). Musculoskeletal loads in ergometer rowing. *Journal of Applied Biomechanics, 20*, 317–323.
Kleshnev, V. (2003). Q&A. *Rowing Biomechanics Newsletter, 3*, 1.
Lamb, D. H. (1989). A kinematic comparison of ergometer and on-water rowing. *American Journal of Sports Medicine, 17*, 367–373.
MacFarlane, D., Edmond, I., & Walmsley, A. (1997). Instrumentation of an ergometer to monitor the reliability of rowing performance. *Journal of Sports Sciences, 15*, 167–173.
McGregor, A. H., Bull, A. M., & Byng-Maddick, R. (2004). A comparison of rowing technique at different stroke rates: A description of sequencing, force production and kinematics. *International Journal of Sports Medicine, 25*, 465–470.
Nolte, V. (2005). *Rowing faster*. Champaign, USA: Human Kinetics Publishers.
Novak, D., Ziherl, J., Olenšek, A., Milavec, M., Podobnik, J., Mihelj, M., et al (2010). Psychophysiological responses to robotic rehabilitation tasks in stroke. *IEEE Transactions in Neural Systems and Rehabilitation Engineering, 18*, 351–361.
Page, P., & Hawkins, D. (2003). A real-time biomechanical feedback system for training rowers. *Sports Engineering, 6*, 67–79.
Pudlo, P., Pinti, A., & Lepoutre, F. (2005). Experimental laboratory apparatus to analyze kinematics and 3D kinetics in rowing. *Sports Engineering, 8*, 39–46.
Redgrave, S. (1995). *Complete book of rowing*. Saint Cloud, GB: Partridge Press.
Rosow, E. (1991). A comparative study of rowing biomechanics. *Proceedings of the 17th Annual Northeast Bioengineering Conference* (pp. 271–272). USA.
Rumball, J. S., Lebrun, C. M., Di Ciacca, S. R., & Orlando, K. (2005). Rowing injuries. *Sports Medicine, 35*, 537–555.
Sciavicco, L., & Siciliano, B. (2001). *Modelling and control of robot manipulators*. Springer.
Tzetzis, G., Mantis, K., Zachopoulou, E., & Kioumourtzoglou, E. (1999). The effect of modeling and verbal feedback on skill learning. *Journal of Human Movement Studies, 36*, 137–151.