Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

Aurora Haug

Mechanical Energy in Rowing

The Individual and Combined Effect of Stroke Rate and Intensity on Joint Power and Mechanical Body Power

Master's thesis in Human Movement Science
Supervisor: Prof. Gertjan Ettema
June 2020

NTNU
Norwegian University of
Science and Technology

Aurora Haug

Mechanical Energy in Rowing

The Individual and Combined Effect of Stroke Rate and Intensity on Joint Power and Mechanical Body Power

Master’s thesis in Human Movement Science
Supervisor: Prof. Gertjan Ettema
June 2020

Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

NTNU
Norwegian University of
Science and Technology

Sammendrag

Hensikt: Hovedmålet med dette studiet var å sammenlikne teknikk ved roing på lav, moderat og høy intensitet og frekvens. Den individuelle og kombinerte effekten av økt frekvens og intensitet på leddspesifikk kraftutvikling og kroppens mekaniske kraft ble undersøkt. Tids-profilene til kraften fra disse leddene og kroppen ble også sammenliknet, ved roing på lav og høy intensitet og frekvens. **Metode:** Tolv erfarne, mannlige roere (alder 23.8 ± 1.9 år; kroppshøyde 189.2 ± 5.5 cm; kroppsvekt 92.3 ± 9.0 kg) deltok i studien. De gjennomførte protokollen som bestod av ni ulike steg, der tre frekvenser og tre intensiteter (lav, moderat og høy) ble kombinert på ulike måter. Hele protokollen ble gjennomført på et dynamisk (RP3) ergometer. Leddspesifikk kraftutvikling og kroppens mekaniske kraft ble beregnet ved hjelp inverse dynamics, basert på kinematiske målinger og kraft på fotbrett og håndtak. En lineær sammensatt modell ble utført for å vurdere den individuelle og kombinerte effekten av frekvens og intensitet på leddspesifikk og kroppens kraftutvikling. For å sammenlikne disse variablene på selvvalgt lav, moderat og høy frekvens og intensitet ble en en-veis ANOVA utført. Til slutt ble tid-profilene til disse variablene ved roing på lav og høy intensitet og frekvens sammenliknet ved hjelp av en SPM analyse. **Resultat:** De tre målte frekvenser og intensiteter var alle signifikant forskjellige fra hverandre, og det var ingen overlapp mellom de tre kategoriene (L, M og H). Relativ drive-time ble redusert med intensitet og økte med stroke rate. Kroppens kraft fluktuerte gjennom hele ro-syklusen. Verdiene var imidlertid små sammenliknet med leddspesifikk kraftutvikling. Hofteleddet ble funnet til å være den viktigste bidragsyteren til fremdrift, mens kneleddet viste negative gjennomsnittsverdier. En hoved effekt av frekvens ble funnet på gjennomsnittlig og relativ leddspesifikk kraft fra ankel, skulder og albue, og relativ leddspesifikk kraft fra kneleddet. Intensitet viste en hoved effekt på alle gjennomsnittlige leddspesifikke krefter, unntatt skulder. En effekt av intensitet ble også funnet på relativ leddkraft i ankel, skulder og albue. Tidsprofilene for alle ledd og kroppskraft viste signifikante forskjeller ved lav og høy intensitet, både under drive og recovery. Sammenligninger av roing med lav, moderat og høy intensitet og frekvens viste at gjennomsnittlig ledd-spesifikk kraft fra alle ledd bortsett fra skulder økte fra lav til høy. Relativ leddkraft endret seg imidlertid ikke. **Konklusjon:** Økt frekvens og intensitet viste signifikant effekt på ledd-spesifikk kraft og kroppens kraftutvikling. Effektene ser derimot ut til å bli kansellert når man sammenlikner selvvalgt lav, moderat og høy intensitet og frekvens. Generelt ser det ut til at å ro på lav og moderat frekvens og intensitet likner på å ro på høy frekvens og intensitet, men med subtile forskjeller.

Abstract

Purpose: The main purpose of this study was to compare technique while rowing at low, moderate and high intensity and stroke rate. The individual and combined effects of stroke rate and intensity on joint power and mechanical body power was investigated. The time-profiles of these joint powers and body power while rowing at self-chosen low and high intensity and stroke rate were also compared. **Methods:** Twelve male, experience rowers (age 23.8 ± 1.9 years; height 189.2 ± 5.5 cm; body mass 9.3 ± 9.0 kg) participated in the study. The experimental protocol included nine conditions, where three stroke rates and three intensities (low, moderate and high) were combined. Rowing was performed on a dynamic (RP3) ergometer. Joint power and body power were estimated via inverse dynamics, based on kinematic measurements and forces at stretcher and handle. A linear mixed model was performed to determine the individual and combined effect of stroke rate and intensity on joint and body power. To compare rowing at self-chosen low, moderate and high stroke rate and intensity, a one-way ANOVA was conducted. The time-profiles of joint powers and body power at high and low stroke rate and intensity were compared using a SPM analysis. **Results:** The three measured stroke rates and intensities were all significantly different from each other, and there were no overlaps between the three categories (L, M and H). Relative drive time decreased with intensity and increased with stroke rate. Body power fluctuated through the cycle. However, the values were small, compared to joint powers. The hip joint was found to be the main contributor to propulsive power, while the knee joint displayed negative average values. A main effect of stroke rate was found on average and relative joint power of ankle, shoulder and elbow, and relative knee joint power. Intensity showed a main effect on all average joints except the shoulder, as well as relative joint power of ankle, shoulder and elbow. The time-profiles of all joints and body power showed significant differences at low and high intensity, during both the drive and recovery. Comparisons of rowing at low, moderate and high intensity and stroke rate showed that all average joint powers except the shoulder increased from low to high. Relative joint power, however, did not change. **Conclusion:** Increasing intensity and stroke rate showed significant effects on joint and body power. However, the effects seem to be cancelled out when comparing rowing at self-chosen low, moderate and high intensity and stroke rate. In general, rowing at low and moderate stroke rate and intensity compares to rowing at high stroke rate and intensity, but with subtle differences.

Acknowledgement

I would like to thank my supervisor, Prof. Gertjan Ettema, for all his help and guidance, as well as valuable insight into the field of study. I would also like to thank my co-supervisor Jørgen Danielsen, for guidance and assistance in the laboratory and Xiangchun Tan for technical support throughout this year. Furthermore, I would like to thank Tonje Pedersen Ludvigsen, my fellow student and partner in this study, for all her support and help. Last, but not least, I would like to thank all the rowers who participated in the study.

Table of Contents

1. Introduction

Rowing is a complex and demanding sport, which places great demands on the athlete's physical capacity and technical skills. A rowing competition is usually held over a distance of 2,000 meters, a distance it takes an experienced rower 5-7 minutes to cover, depending on gender, weight classification, boat type and weather conditions (1). During a race, the rowers usually row at a frequency of 35-45 strokes per minute (2), with a power output of 500 W (3). Training in rowing is highly varied, ranging from low intensity with long duration to more race-specific training at high intensity (4). Increasing intensity in rowing is achieved through increasing both stroke rate and power output. The utilization of rowing ergometers is widespread, and there are even held separate championships and competitions for ergometer rowing. Ergometers are also commonly used for performance testing, training out of season or during poor weather and research (5).

The rowing cycle, often referred to as "the stroke cycle", can be divided into two phases; *drive* and *recovery.* The drive starts with the catch, where the rower places the oar blades in the water. At the catch the rower sits in a flexed position, closest to the stern of the boat (or flywheel on an ergometer). The drive is the propulsive part of the stroke cycle, during which rower extends the lower limbs and exerts force on the foot stretcher and handle to propel the boat. The drive ends with the finish, where the rower is at its closest to the bow of the boat, and the oar blades is pulled out of the water. The cycle then continues with the recovery. During recovery, the oars are out of the water and the rower returns to the initial position; the catch (6).

Time to complete 2,000 m is the definitive measure of performance in rowing. Therefore, it is critical that the rower achieves a high average velocity of the boat during the race(5). Performance in rowing, and therefore velocity, correlates with several physiological factors, such as maximal oxygen uptake, power output at 4.0 mmol/l lactate and percentage of slow twitch fibres (1, 4). However, among rowers with similar physical capacity, performance can be affected by technique (7). Furthermore, average velocity depends on the power the rower generates, the utilization of this power to propulsion and the efficiency of the propulsive power (8). The rower's technique is of importance, as this affects both the magnitude and effectiveness of propulsive power (9). Identified aspects of rowing technique important for performance includes consistency of the propulsive work, smoothness of the stroke, stroke-to-stroke consistency and mean propulsive power output per kg body mass (10).

Propulsion of the boat depends on the ability the rower has to develop large forces at the foot stretcher and transfer those forces to the oar via the handle. An effective transfer of stretcher force to handle force is enhanced by the rowers' technique (11). The drive is initiated by a forceful extension of the knees, followed by hip extension and later movement of the trunk, shoulders and elbows. A proper sequencing of the limbs increases the force developed at the stretcher and the amount of this force transferred to the handle and oars. Furthermore, kinematics of the knee and hip are important for stretcher force production and the transfer of stretcher force to the handle (12). Previous research found that the lower limbs, especially the hips, produces the greatest magnitude of power during the stroke cycle (13, 14), while the upper limbs contributes only to 15-25% of the total propulsive power (15). Increasing stroke rate showed no effect on average knee joint power (16), while the relative contribution of shoulder and elbow joint power decreased when stroke rate increased (15).

As described, the rower moves back and forth in relation to the boat during the stroke. Because of this, the velocity of the boat is not constant, but fluctuates throughout the stroke (5, 11, 17). Hofmijster et al. (6), found that these fluctuations increases when average velocity increases, but that overall rowing seems to become more efficient at higher stroke rate and power output. However, the fluctuations in velocity is negative for performance, and the rower should therefore aim at adopting a technique which reduces the fluctuations (17). During steady-state rowing, there will be no net change in the mechanical energy of the body from cycle to cycle, because the rower returns to its initial position. The energy of the rowers' body does however vary throughout the stroke cycle, and there appears to exist energy exchanges between the rower and boat (and vice versa). This exchange can affect the fluctuations in velocity of the boat (18). Therefore, it is important to understand how the mechanical energy of the rowers' body varies throughout the cycle.

Previous studies investigating rowing technique have found that a higher average boat velocity is achieved through increasing both stroke rate and power output (5, 19, 20). Even though the presented research suggests the rower's technique is altered when stroke rate and power output increases, the mechanisms and sources behind these changes are not clear. Changing both the stroke rate and power output will likely lead to technical adaptations which are joint specific. Therefore, the investigation of joint powers across stroke rates and power outputs can also provide insight into the coordinative strategies the rower utilizes. To the author's knowledge, no previous research has been aimed at understanding or separating the individual and combined effect of stroke rate and power output on technique in rowing. This effect is important to understand, as a step on the way to determining an optimal technique.

Increasing the understanding of this effect will also increase the knowledge of the differences and similarities between the technique at different stroke rates and power outputs used in training and competition in rowing.

Therefore, the main aim of this study is to compare technique while rowing at low, moderate and high stroke rate and intensity. This will be done by investigating the individual and combined effects of stroke rate and intensity on joint specific power and mechanical power of the body. Furthermore, this study will investigate the time profiles of these joint powers and mechanical power of the body, over the stroke cycle.

2. Materials and Methods

2.1 Participants

Twelve male elite and sub-elite rowers participated in the study (mean ± SD: age 23.8 ± 1.9 years; height 189.2 ± 5.5 cm; body mass 92.3 ± 9.0 kg). The participants had on average 8.4 ± 4.5 years of rowing experience and were familiar with ergometer rowing. Their performance time on Concept2-ergometer 2000m was on average 06:08 (min:sec), ranging from 05:56 to 06:28. The participants were recruited through the Norwegian national team and a student club in Norway. The Norwegian Centre for Research Data approved the study. Informed written consent was obtained from each participant prior to testing. All participants were informed about the aim of the study, and that withdrawal was possible at any point.

2.2 Experimental Protocol

After a 10-minute warm-up and familiarization on the ergometer, all participants carried out the experimental protocol. The protocol included nine conditions: three at high intensity, three at moderate intensity and three at low intensity, at varying stroke rates. The conditions at high intensity had a duration of 1.5 minutes and the conditions at moderate and low intensity lasted for 4 minutes. To avoid fatigue and its possible effect on the rowers' technique, the breaks between each condition was 2-5 minutes. Instructions before, and feedback during the testing were standardized and given by the same researcher throughout the data collection. A timeline of the entire protocol is presented in Figure 1.

The first three conditions were defined as the "self-chosen" conditions, meaning they were similar to training and competition in rowing. These followed the same order for all participants: 1) *High intensity and high stroke rate (HH)*. The participants were instructed to row at a power output and stroke rate corresponding to a 2000m-trial. This condition was used to determine intensity for the remaining conditions, and high stroke rate. Intensity was defined as power output, measured in watts [W]. 2) *Low intensity and low stroke rate (LL).* The participants were instructed to keep an intensity corresponding to 55% of the intensity on the first condition at a self-chosen stroke rate. 3) *Moderate intensity and moderate stroke rate (MM),* corresponding to 75% of the intensity at the first condition at a self-chosen stroke rate. The three intensities and three self-chosen stroke rates were then combined for the remaining six conditions, in the following ways: low intensity – moderate stroke rate (LM), low intensity – high stroke rate (LH), moderate intensity – low stroke rate (ML), moderate intensity – high stroke rate (MH), high intensity – low stroke (HL) rate and high intensity – moderate stroke rate (HM). These six conditions were performed in a semi-randomized order for all participants, i.e., the intensities were kept in the same order for all participants, while the stroke rates were randomized.

Kinematic and kinetic data were collected during each condition. Besides these data, also EMG were recorded for eight muscles on the upper and lower limb, as well as blood lactate after all conditions and respiratory data during the conditions at low and moderate intensity. The current study is part of a larger research project, and only kinetic and kinematic data relevant for this paper will be presented.

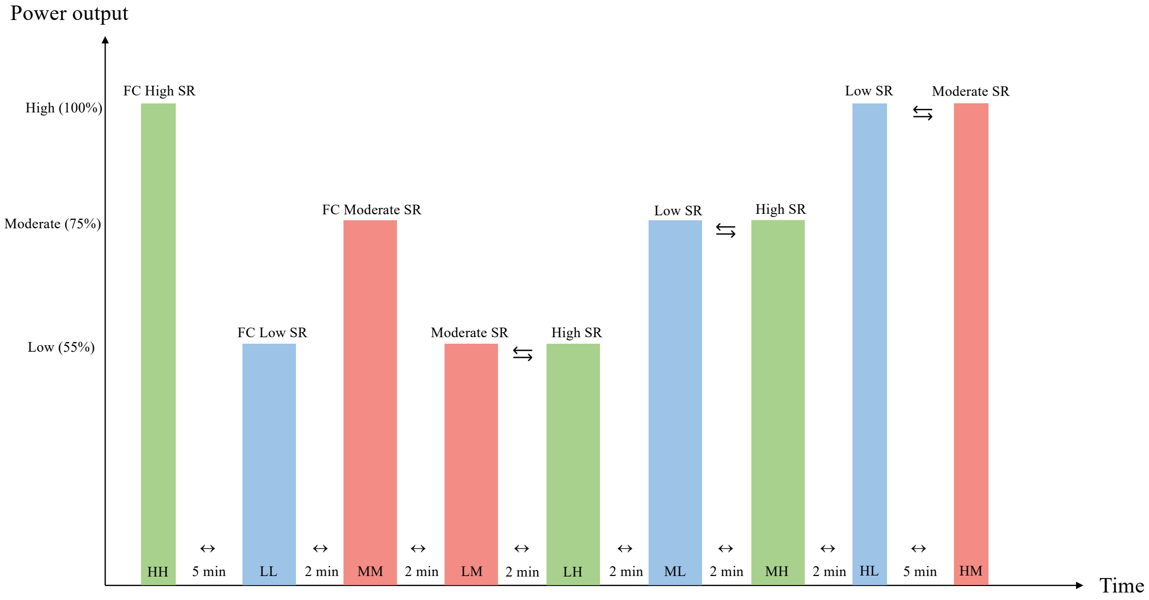

Figure 1 Schematic presentation of the entire protocol, showing how the conditions were spread out over time. Note that the timeline shows one order of stroke rates. Arrows between LM and LH, ML and MH and HL and HM indicate that the order was randomized for each participant. Arrows between each condition indicate break time. SR = stroke rate, FC = freely chosen. H = high, M = moderate, L = low. The first letter indicates intensity, and the second letter indicates stroke rate.

2.3 Equipment and Measurements

2.3.1 Ergometer

Rowing was performed on a Row Perfect 3 (RP3) ergometer (Care RowPerfect3 Bv., The Netherlands). This ergometer is dynamic, meaning that both the seat and the flywheel with the stretcher move. This is in contrast to a conventional static ergometer where the flywheel and stretcher is fixed, and only the seat moves. To minimize manipulation of the rower's habitual technique the participants set an individual damper setting on the flywheel, based on personal preference. This setting was kept the same throughout the protocol (i.e. at all conditions). A mobile phone (Samsung Electronics Co., Ltd., Suwon, South-Korea) connected to the ergometer, displayed stroke rate and power output per stroke, on the RP3 Rowing app (RP3 Rowing). This allowed the rower to adhere to the instructed stroke rate and intensity for each condition.

2.3.2 Kinematic Measurements

Three dimensional kinematic measurements were obtained using ten infrared Oqus cameras (Qualisys AB, Gothenburg, Sweden) capturing the position of passive reflective markers. The reflective markers were placed on both the participant and equipment. Bilateral symmetry of movement was assumed, and markers were placed only at the left side of the equipment and participant, using double-sided tape (3M Company, Minnesota, USA). Eight markers were fixed to the ergometer and two markers were fixed to each force plate. Figure 2 shows a schematic presentation of the setup of the equipment, including the placement of the markers. Twelve markers were placed on the participants body, on the following anatomical landmarks; base of 5th metatarsal, lateral malleolus, lateral epicondyle of femur, greater trochanter, iliac crest, posterior superior iliac spine, 5th lumbar vertebra, 7th thoracic vertebra, 7th cervical vertebra, lateral edge of acromion process, lateral epicondyle of humerus and styloid process of radius. The markers were placed by the same person throughout the data collection. At the start of each day of testing the system was calibrated, using a wand and L-frame (Qualisys AB, Gothenburg, Sweden). Kinematic data were sampled at 100 Hz, low pass filtered (8th order, Chebyshev Type II filter, cut-off 15 Hz) and synchronized with kinetic and EMG measurements using Qualisys Track Manager (QTM; Qualisys AB, Gothenburg, Sweden).

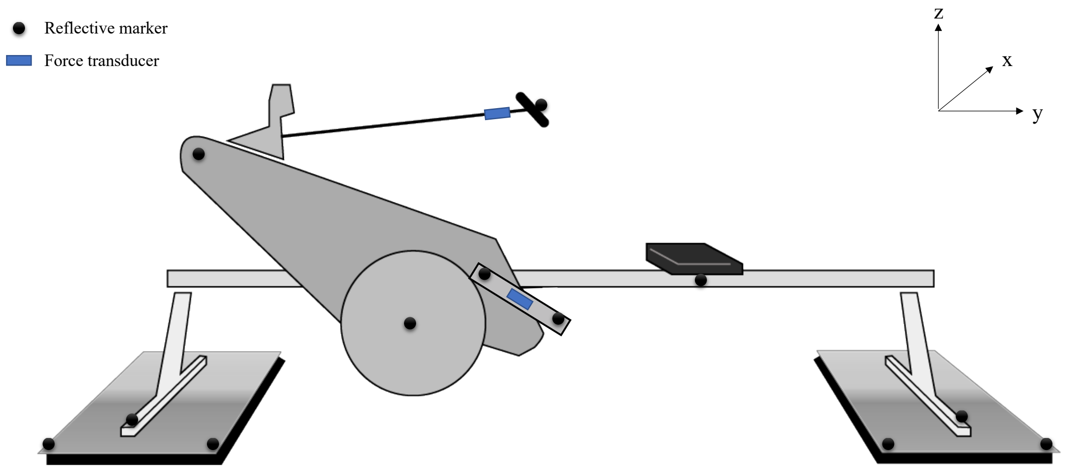

Figure 2 A graphic representation of the setup of the equipment. The figure shows the ergometer with reflective markers, load cell and force plates

2.3.3 Kinetic Measurements

The rowing ergometer was instrumented to measure external forces: force at the handle, stretcher and seat. A free body diagram of the rower with the external forces are presented in Figure 3. Handle force (F_{handle}) was measured using a load cell (N-DTS-FS5, Noraxon USA Inc., Scottsdale, Arizona). To measure stretcher force ($F_{stretcher}$) a custom-made force-plate existing of three 3D Kistler force cells (Kistler Instruments AG, Winterthur, Switzerland) was mounted on the foot-stretchers. The load cell and custom-made force-plate were calibrated against a range of forces of known magnitude (5 to 100 kg). The ergometer was placed on two Kistler force-plates (Kistler 9286BA, Kistler Instruments AG, Winterthur, Switzerland) to measure forces at the seat (F_{seat}). Before each measurement all kinetic measurements were zeroed, and offset were removed at the start of each measurement. Kinetic data were sampled at 200 Hz and low pass-filtered (8th order, Chebyshev Type II filter, cut-off 15 Hz). Kinematic and kinetic data were recorded during the first 1.5 minutes of each condition.

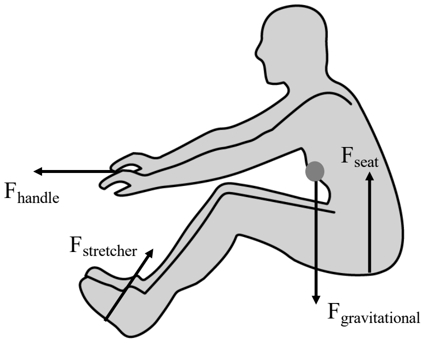

Figure 3 Free body of the rower, with external forces acting on the rower: handle force, stretcher force, seat force and gravitational force. Redrawn from Hofmijster et al. (21).

2.4 Data Analysis

The body was modelled as a system of rigid bodies, linked by frictionless joints. Segments in the sagittal plane were defined as forearm, upper arm, trunk, thigh, leg and foot. Segments were defined as a link between two markers; e.g. the trunk was defined as the link between the hip and shoulder marker. The current study is part of a larger study that also allows closer inspection of trunk motion. Therefore, some of the markers on the pelvis and spine were not used in this study. The kinematic data were used to determine joints' centre position of elbow, shoulder, hip, knee and ankle, as well as the segments' motion. Equations based on anthropometric data according to de Leva (22), segment lengths and individual body mass were applied to estimate moment of inertia, mass and centre of mass of the segments. Calculation of linear and angular velocities and acceleration of segments were done by numerical differentiation of position data. The position data from the left side of the body was presumed to represent the average of the left and right side, since bilateral movement symmetry was assumed. Inverse dynamics methods (23) were applied to estimate joint moments, which, by multiplying these with joint angular velocity yield joint power. In brief, the inverse dynamics analysis starts at a distal segment, for which (distal) external moments and forces are known. Applying Newton's equations of motion on this segment allows for the estimation of the unknown (proximal) joint forces and moment. These joint forces and moment are then implemented for solving Newton's equation for the next, more proximal, segment resolving forces and moments at the adjacent joint. $F_{stretcher}$ was used as external force to calculate joint power at ankle, knee and hip. Elbow and shoulder joint power was calculated on the basis of F_{handle}. For the lower extremity, joint power was estimated on the basis of dynamics in the sagittal plane, for the upper extremity this was done in both sagittal and transverse plane. Power in these two planes were summated according to the Pythagorean principle (24).

Total body mechanical energy (E_{body}) was calculated as the sum of total energy of all segments:

$$E_{body} = \sum_{i=1}^{6} E_i$$

Where E_i is the total energy of segment *i:*

$$E_i = m_i g h_i + \frac{1}{2} m_i v_i^2 + \frac{1}{2} I_i \omega_i^2$$

Where m_i is segment mass [kg], g is gravitational acceleration [-9.81 $m \cdot s^{-2}$], h_i is height of segment above the ground [m], v_i is velocity of the segment [$m \cdot s^{-1}$], I_i is moment of inertia of the segment [kg·m^2] and ω_I is angular velocity of the segment [rad/s]. Body power (P_{body}) was calculated by differentiation of E_{body} with respect to time. Thus, P_{body} reflects the rate of change in E_{body}. Average P_{body} over a cycle will likely be zero. Therefore, maximal body power ($MaxP_{body}$) was calculated to reflect the change in body power.

Handle power (P_{handle}) was calculated as F_{handle} multiplied by handle velocity. Stretcher power ($P_{stretcher}$) was calculated as $F_{stretcher}$ multiplied by stretcher velocity. The power output which is used in propulsion (P_{prop}) was calculated by F_{handle} multiplied by the extraction velocity of the cord (as determined by motion of handle relative to stretcher). F_{seat} was estimated by force measured at the force plates, F_{handle}, motions of the rower's CoM and flywheel system. Power applied by the rower at the seat due to friction force resisting motion (P_{seat}) was estimated with the use of F_{seat}. Relative contribution from each joint (relative joint power) was calculated as the percentage of the joint to total propulsive power.

One cycle was defined on the basis of displacement of the handle relative to the flywheel. The catch was defined as the position where the handle was closest to the flywheel, and the finish was where the handle was furthest away from the flywheel. The period between catch and finish was defined as the drive phase, while the recovery phase was the period between the finish and the catch. Stroke rate (SR) was defined as the number of cycles per minute (strokes·min^{-1}), cycle time (CT) as the time elapsed for each cycle, drive time (DT) as the duration of the drive phase, recovery time (RT) as the duration of the recovery phase and relative drive time (DT rel.) as the percentage of drive time to total cycle time.

To ensure a period of steady pace rowing (with steady power output and SR) was analysed, 20-30 cycles at the end of each measurements were used in the analysis. All variables were first averaged and time-normalised over the entire cycle for each participant at each condition, and later averaged across participants. Time normalization was performed by resampling each variable to 200 samples ranging from 0 to 100% cycle time. All data were stored offline and processed in MATLAB (9.5.0 R2018b, Mathworks Inc., Natick, MA, USA).

2.5 Statistical analysis

A linear mixed model was executed to evaluate the individual and combined effect of stroke rate and intensity on cycle characteristics, joint powers and body power. To determine whether the participants adhered to the instructed stroke rate and intensity, a post hoc test with Bonferroni adjustments was performed to determine the location of the effect. Replacing the post hoc testing for joint power variables, a one-way analysis of variance (ANOVA) was performed. This test was performed comparing the three self-chosen conditions (LL, MM and HH), which were the conditions of interest in accordance to the study aim. Statistical parametric mapping (SPM, (25)) was used to statistically compare time profiles of joint power and body power, at HH and LL. This was done to provide additional insight into the time location of the effects tested in the linear mixed model. HH and LL were the conditions of most interest for this comparison, because they correspond to competition and low-intensity training.

Statistical significance was set at $p < 0.05$ for all tests. Data are presented as means ± standard deviation (SD). Missing data was handled using regression imputation, as described by Bland (26). This approach is acceptable in situations where the data are missing completely at random (MCAR). This was the case in the present study, where some data were lost due to technical errors and equipment failure. The statistical analysis was carried out using Statistical Package for the Social Sciences (SPSS 26; Chicago, USA), MATLAB (9.5.0 R2018b, Mathworks Inc., Natick, MA, USA) and Microsoft Excel for Mac (Excel 2019, 16.34, Microsoft Corp., Redmond, WA, USA). The SPM analysis were conducted in MATLAB using the open source spm1d code (v.M0.1, www.spm1d.org).

3. Results

3.1 Cycle Characteristics

3.1.1 Stroke Rate and Time-related Variables

The average stroke rates measured at each condition are presented in Figure 4. Other time-related cycle characteristics are presented in Table 1. A main effect of stroke rate ($p < 0.001$) and intensity ($p < 0.01$) on stroke rate was found. Post hoc analysis showed that in all cases, the three SR outcomes in one “SR instruction category” (L, M, H) were significantly different from all SR outcomes in other instruction categories ($p < 0.01$ for all results). Stroke rates at LL (24.8 ±2.46), MM (30.2 ±2.52) and HH (35.9 ±2.48) were all significantly different from each other (Table 4). DT and RT significantly decreased, while DT rel. increased when stroke rate increased. DT and DT rel. significantly decreased with increasing intensity. An interaction effect of stroke rate and intensity on DT was found (Table 1).

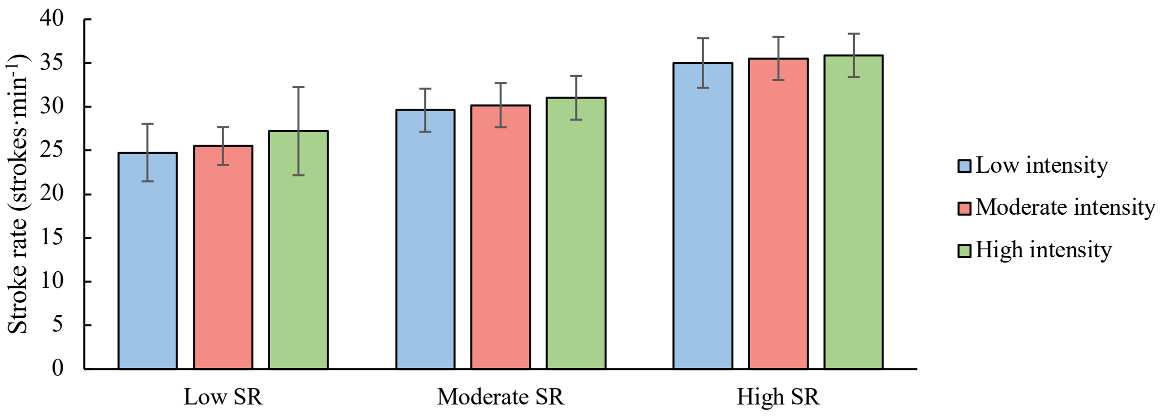

Figure 4 Average stroke rate measured during ergometer rowing, at nine different conditions. Each bar represents one condition. Error bars are ± 1 SD.

Table 1 Time-related cycle characteristics at the nine conditions

Stroke rate	Low			Moderate			High		
Intensity	Low	Mod	High	Low	Mod	High	Low	Mod	High
DT (s) A***, B***, C*	0.94 ±0.08	0.84 ±0.06	0.79 ±0.06	0.91 ±0.06	0.84 ±0.05	0.76 ±0.05	0.87 ±0.06	0.81 ±0.05	0.75 ±0.04
RT (s) A***	1.52 ±0.31	1.52 ±0.18	1.47 ±0.32	1.13 ±0.14	1.16 ±0.15	1.19 ±0.14	0.86 ±0.13	0.89 ±0.11	0.93 ±0.09
DT rel. (%) A***, B***	38.8 ±6.38	35.8 ±2.75	35.9 ±7.91	44.6 ±2.67	42.2 ±2.88	39.2 ±2.35	50.3 ±3.75	47.7 ±2.93	45.0 ±2.07

Values are mean ±1SD. DT drive time; RT recovery time; DT rel. relative drive time.
A = sig. for stroke rate, B = sig. for intensity, C = sig. for interaction of stroke rate and intensity.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3.1.2 Intensity and Other Power-related Variables

Figure 5 shows the average intensity (i.e. propulsive power; P_{prop}) measured at each condition. Other power-related variables are presented in Table 2. A main effect of intensity ($p < 0.001$) and stroke rate ($p < 0.05$) on P_{prop} was found. However, the three intensity outcomes in one instruction category (L, M, H) were significantly different from all intensities in other instruction categories ($p < 0.001$ for all results). P_{prop} significantly increased from 259.1 W ±33.0 at LL to 345.8 W ±34.7 at MM and 462.3 W ±46.4 at HH (Table 4). A main effect of intensity was also found on P_{handle}, $P_{stretcher}$, and $MaxP_{body}$, while stroke rate had a significant effect on $P_{stretcher}$. An interaction effect of stroke rate and intensity was found on $MaxP_{body}$ (Table 2). $MaxP_{body}$ significantly increased from LL to MM and HH (Table 4).

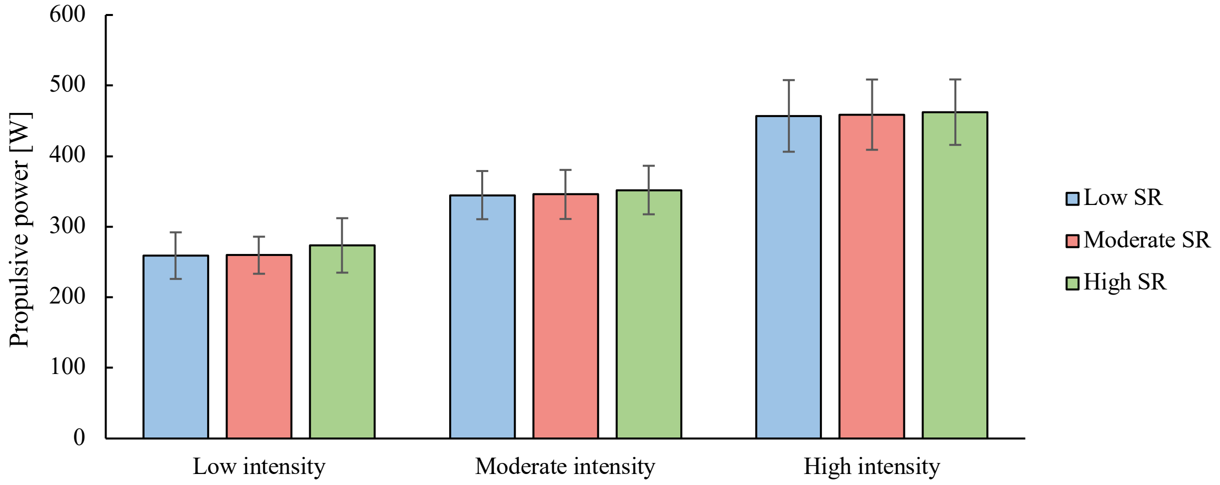

Figure 5 Average propulsive power measured during ergometer rowing, at nine different conditions. Each bar represents one condition. Error bars are ± 1 SD.

Table 2 Power-related cycle characteristics at the nine conditions

Intensity	Low			Moderate			High		
Stroke rate	Low	Mod	High	Low	Mod	High	Low	Mod	High
P_{handle} (W) B***	150.7 ±16.8	150.5 ±11.2	157.3 ±17.4	197.9 ±16.9	198.7 ±16.2	201.6 ±15.4	267.1 ±28.3	261.8 ±25.4	265.8 ±22.7
$P_{stretcher}$ (W) A***, B***	122.7 ±23.1	128.9 ±27.6	132.7 ±27.6	165.4 ±26.7	169.4 ±30.3	175.8 ±28.3	214.7 ±33.7	223.1 ±37.4	227.2 ±40.7
$MaxP_{body}$ B***, C**	230.1 ±70.2	227.0 ±37.4	288.6 ±72.3	343.2 ±89.3	305.1 ±50.4	318.7 ±56.9	476.9 ±109.9	454.7 ±56.9	422.1 ±55.2

Values are mean ±1SD. P_{handle} handle power; $P_{stretcher}$ Stretcher power; $MaxP_{body}$ maximal body power
A = sig. for stroke rate, B = sig. for intensity, C = sig. for interaction of stroke rate and intensity.
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3.2 Example of One Cycle

Figure 6 shows a stick figure of one rower, performing ergometer rowing at high intensity and stroke rate (HH). The red line represents $F_{stretcher}$ and the green line F_{handle}. The vertical, dashed line indicates the end of the drive phase. The figure illustrates the sequential movement of the segments during the stroke; the knee initiates the drive, followed by movement of the hip, trunk, shoulder and elbow. During recovery the sequence is opposite. A visual inspection of the direction of $F_{stretcher}$ and joint movement of the knee during the drive reveals a conflict between the observed moments of the task. The knee extension movement suggests a muscle knee extension moment will occur. However, the stretcher force suggests a muscle knee flexion moment occurs. Additionally, this conflict appears as net negative joint power of the knee (Figure 8, Figure 9).

Time profiles of measured external powers are presented in Figure 7. In general, the patterns appear similar across intensities and stroke rates. However, there are some apparent differences, with both increasing stroke rate and intensity. First of all, the time of power production appears to increase somewhat with increasing stroke rate. This is represented by an increase in relative drive time (Table 1). Secondly, all power profiles' amplitude increases when intensity increases. This is further manifested as an increase in average power with increasing intensity (Table 2). From the figure it is evident that only a small amount of power is produced at the seat (Figure 7D) compared to power produced at the stretcher and handle. The magnitude of P_{body} (Figure 7E) is also small compared to propulsive power (Figure 7A). The pattern of P_{body} and P_{seat} are similar, with one positive peak followed by a negative peak during the drive and both positive and negative values during recovery.

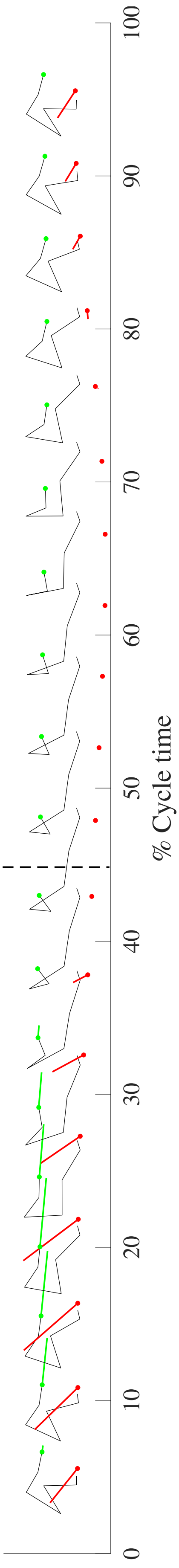

Figure 6 Stick figure of one rower, rowing at high intensity and stroke rate (HH). The green line represents handle force and the red line represents stretcher force.

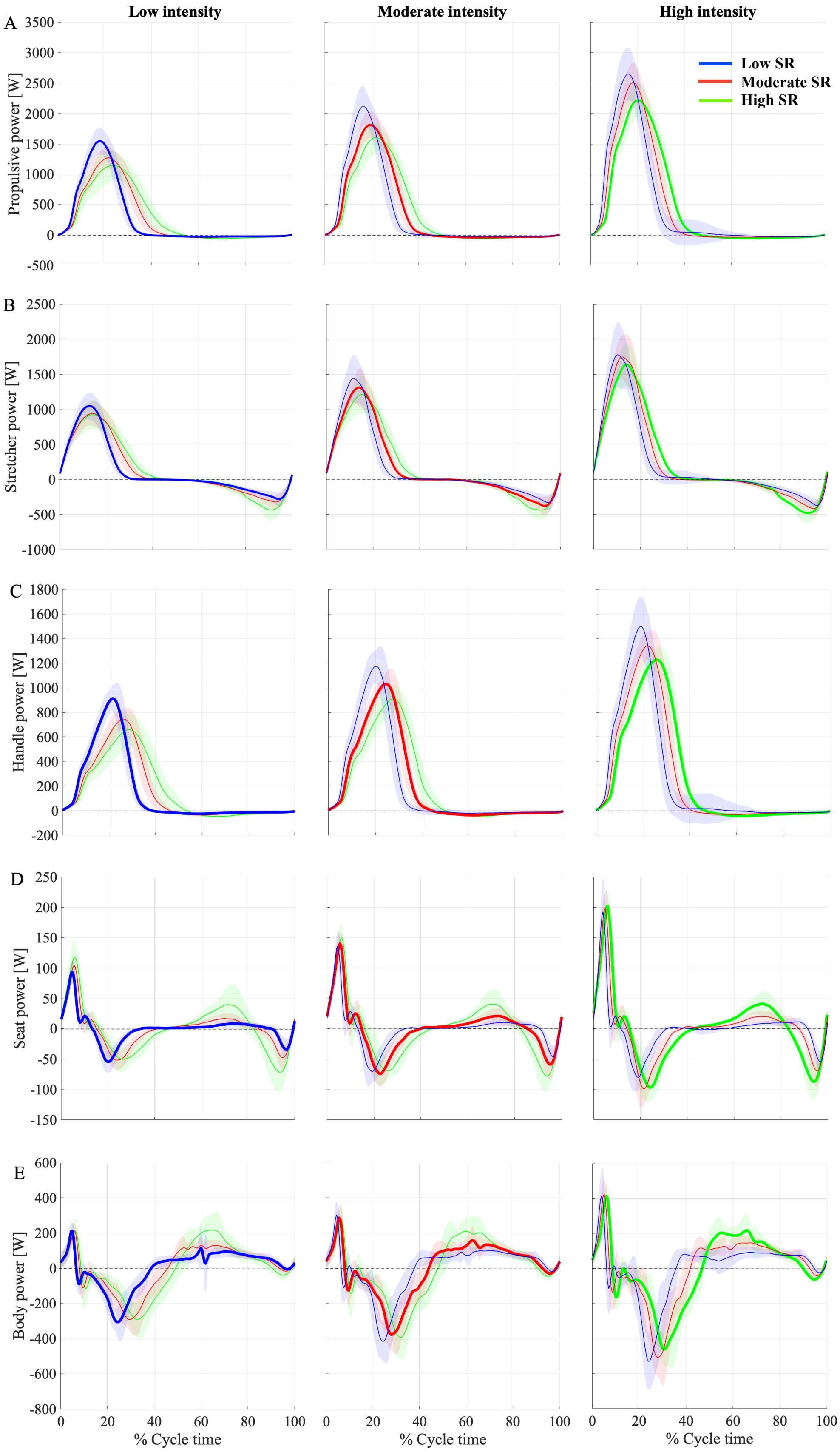

Figure 7 Time profiles of propulsive power (A), stretcher power (B), handle power (C), seat power (D) and body power (E), at the nine conditions. The bold lines highlight the three self-chosen conditions: LL (blue), MM (red) and HH (green). The shaded areas are ±1SD. The legend is shared for all sub-figures.

3.3 Average and Relative Joint Power

The average joint power of each joint at the nine conditions is shown in Figure 8, with statistical results from the linear mixed model presented on the right side of each joint. Table 3 displays the relative contribution from each joint to propulsive power (relative joint power). All joint powers, with the exception of shoulder joint, were significantly affected by intensity. A main effect of stroke rate was found on ankle, shoulder and elbow, as well as on relative joint power of all joints with the exception of the hip (Figure 8, Table 3). The hip joint produced the greatest average power across stroke rates and intensities and was therefore also the main contributor to propulsion (Table 3). It is interesting to note that relative hip joint power was not affected by either stroke rate or intensity. Average and relative knee joint power was negative at all stroke rates and intensities. Both average and relative ankle joint power increased with intensity and decreased with stroke rate.

The average joint power of the shoulder appears to show the largest variation across subjects (evident from a large standard deviation). Even though intensity showed no significant effect on average shoulder joint power, an interesting trend is observable (Figure 8); the effect of intensity on average shoulder joint power seems to be opposite at low and high stroke rate. Average joint power of the elbow increased with both stroke rate and intensity, as well as the interaction of the two. The relative joint power of both the shoulder and elbow decrease with intensity.

Table 3 Relative contribution from the joints to propulsive power, at the nine conditions

Intensity	Low			Moderate			High		
Stroke rate	Low	Mod	High	Low	Mod	High	Low	Mod	High
Rel. P_{ankle} (%) A***, B***	26.8 ±5.3	25.8 ±6.5	23.3 ±4.9	28.2 ±5.4	26.9 ±5.6	25.2 ±5.0	28.7 ±4.8	27.8 ±4.9	26.2 ±4.7
Rel. P_{knee} (%) A**	-67.8 ±15.3	-66.8 ±15.5	-65.2 ±13.2	-67.6 ±12.3	-65.2 ±12.3	-64.1 ±13.6	-65.7 ±9.3	-64.8 ±11.9	-61.9 ±11.2
Rel. P_{hip} (%)	171.9 ±19.8	177.2 ±22.6	173.8 ±21.4	175.5 ±15.7	171.5 ±15.3	172.2 ±18.3	173.4 ±16.2	172.4 ±12.4	169.5 ±14.8
Rel. $P_{shoulder}$ (%) A***, B***, C***	10.6 ±3.9	10.7 ±4.0	10.4 ±4.7	7.2 ±3.8	8.9 ±3.5	8.5 ±4.1	5.1 ±2.8	6.4 ±4.0	8.3 ±3.5
Rel. P_{elbow} (%) A**, B***, C***	10.3 ±2.0	10.3 ±1.8	9.9 ±2.3	8.9 ±1.8	9.9 ±1.8	9.6 ±1.8	8.5 ±1.5	8.5 ±1.8	9.8 ±2.0

Values are mean ±1SD. Rel. P_{ankle} relative ankle joint power; Rel. P_{knee} relative knee joint power; Rel. P_{hip} relative hip joint power; Rel. $P_{shoulder}$ relative shoulder joint power; Rel. P_{elbow} relative elbow joint power. A = sig. for stroke rate, B = sig. for intensity, C = sig. for interaction of stroke rate and intensity. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

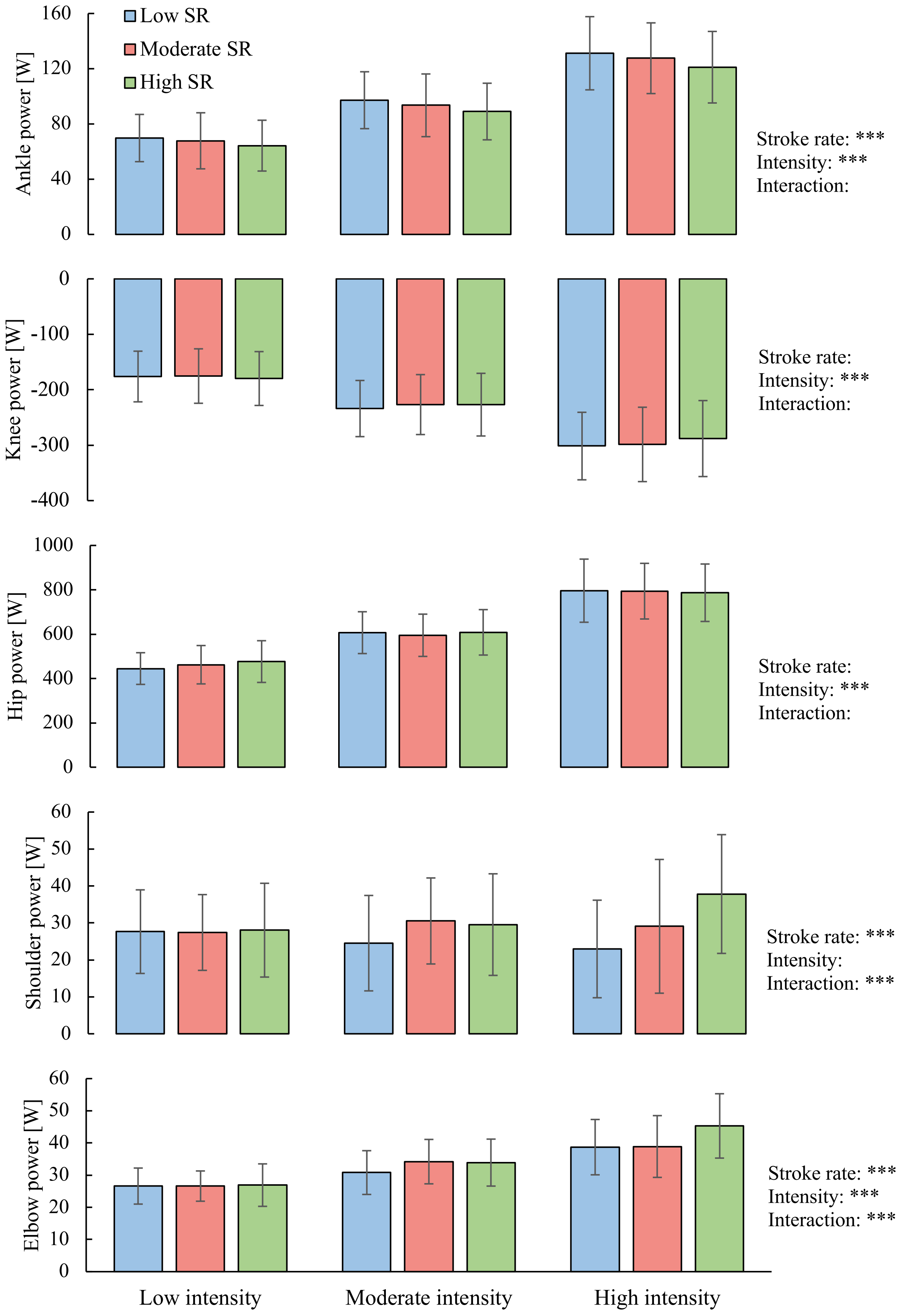

Figure 8 Average joint power of ankle, knee, hip, shoulder and elbow at the nine conditions. Error bars are ±1SD. The legend is shared for all sub-figures. Asterisk indicates statistical significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3.4 Time Profiles of Joint Power

Time traces of joint powers for the nine conditions are presented in Figure 9. The time trace of P_{body} is presented in Figure 7. In general, the overall patterns look similar across stroke rates and intensities for all joints. There are some observable differences of the amplitude of the joint power, that seems to increase with intensity. This is further manifested as an increase in average joint power (Figure 8), and it is evident from the SPM analysis (Figure 10). Figure 9 shows that the lower limbs produce power earlier in the cycle than the upper limbs. From the time profile of the knee it is evident that knee joint power is not negative throughout the cycle. The negative peak in knee joint power occurs at approximately the same time as the positive peak in hip joint power.

Figure 10 shows the results from the SPM analysis comparing time profiles of joint powers and body power at LL and HH. In general, Figure 10 shows that joint power and body power at HH is not higher throughout the cycle. Joint power of all joints showed periods during the first half of the cycle (the drive) where HH was significantly higher than LL. Some of these observed differences are probably related to the increased relative drive time at HH. Of interest is also the significant differences occurring during recovery for all joints except ankle. P_{body} shows several periods throughout the cycle with significant difference between HH and LL. In general, it seems that the positive peaks of P_{body} are higher and the negative peaks are lower at HH compared to LL.

3.5 Comparison of LL, MM and HH

Table 4 shows results from the one-way ANOVA performed to compare average joint power, $MaxP_{body}$, stroke rate and intensity at the three conditions of main interest: LL, MM and HH. This, this analysis is done on a selection of the conditions presented in Figure 8 and Table 3 in order to identify differences due to combined stroke rate and intensity effects. All average joint powers, with the exception of shoulder power increased from LL to HH. However, there was no significant change in relative joint power from LL to MM and HH. Overall, the results suggest that LL and MM are the two conditions most similar to each other, in terms of average and relative joint power. However, both LL and MM show the same significant differences when compared to HH.

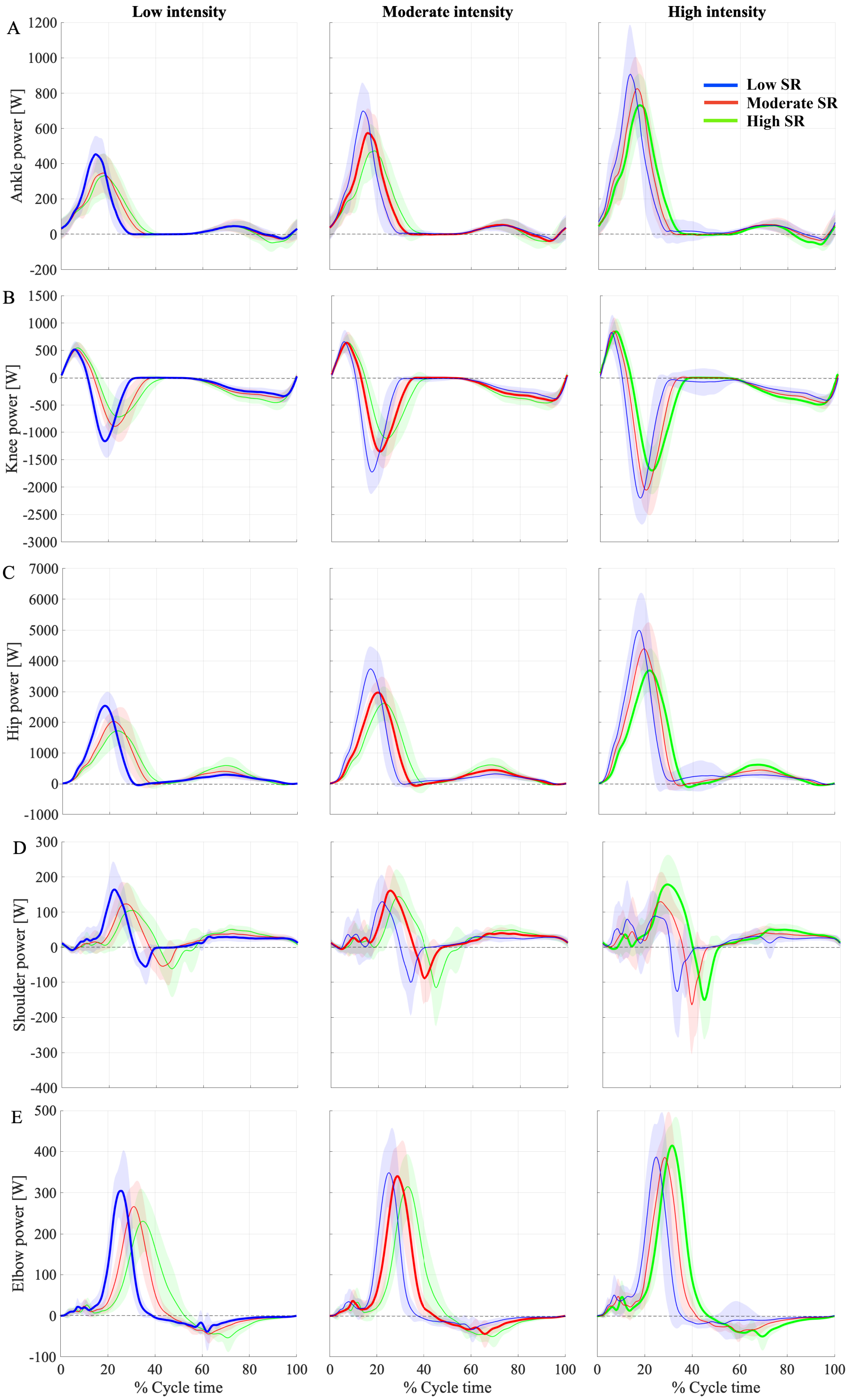

Figure 9 Time profiles of joint power of ankle (A), knee (B), hip (C), shoulder (D) and elbow (E) at the nine conditions. The bold lines highlight the three self-chosen conditions: LL (blue), MM (red) and HH (green). The shaded areas are ±1SD. The legend is shared for all sub-figures.

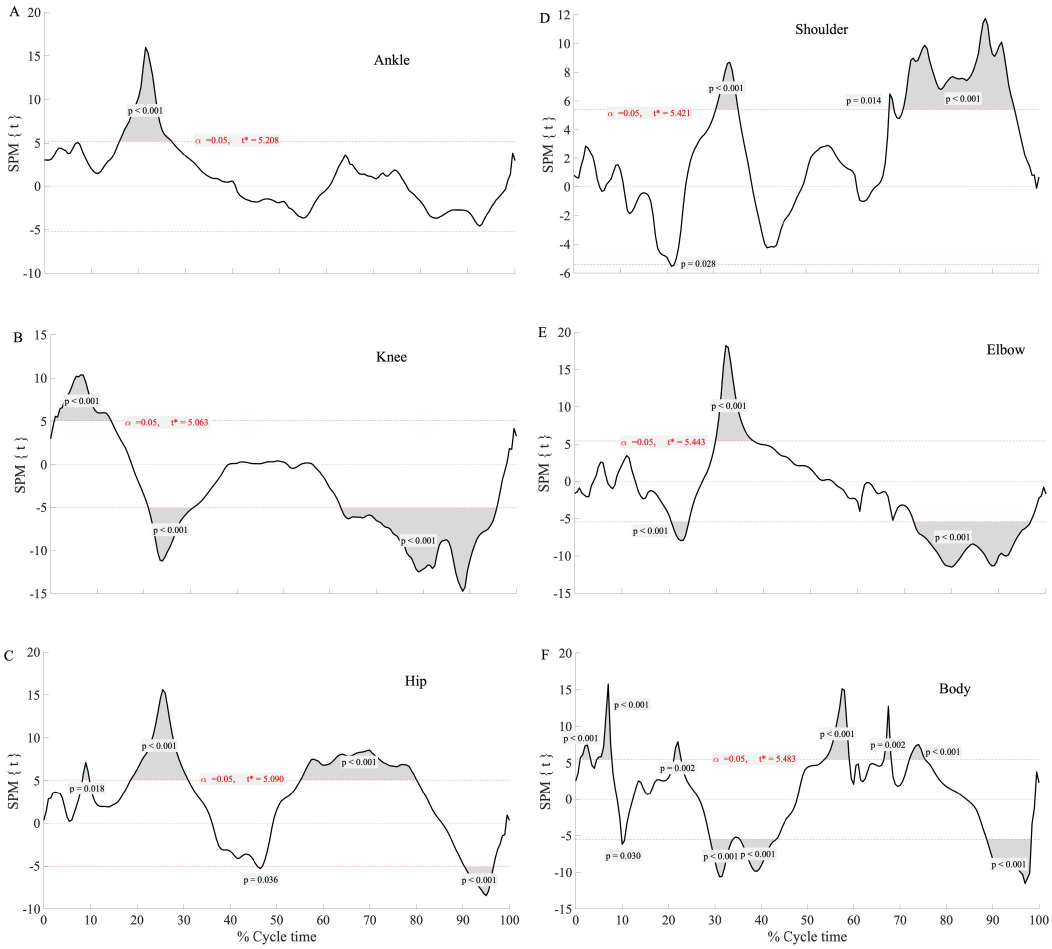

Figure 10 Results from SPM analysis, illustrating where joint specific power (A-E) and body power (F) at HH were greater (+) and less (-) than at LL. The dotted line indicates the critical threshold for statistical significance.

Table 4 Results from one-way ANOVA comparing LL, MM and HH.

Comparisons	LL – MM	MM – HH	LL – HH
Stroke rate	***	***	***
Power output	***	***	***
P_{ankle} Rel. P_{ankle}	* -	** -	*** -
P_{knee} Rel. P_{knee}	- -	* -	*** -
P_{hip} Rel. P_{hip}	** -	*** -	*** -
$P_{shoulder}$ Rel. $P_{shoulder}$	- -	- -	- -
P_{elbow} Rel. P_{elbow}	- -	** -	*** -
$MaxP_{body}$	*	***	***

Asterisk indicate statistical significance, – indicate not significant. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4. Discussion

4.1 Main Results

The main aim of this study was to compare technique while rowing at low, moderate and high intensity and stroke rate (i.e. LL, MM and HH). Second, this study investigated the individual and combined effect of stroke rate and intensity on joint specific power and mechanical body power. The time profiles of these variables at LL and HH were also compared. The main findings of the study are that average joint power of all joints except the shoulder significantly increased from LL to HH. Relative joint power, however, was not significantly changed from LL to HH. Not surprisingly, intensity was found to have the greatest effect on average joint power, but stroke rate showed the greatest effect on relative joint power. Lastly, the time profiles of all joint powers and body power showed periods of both similarities and significant differences throughout the cycle.

4.2 Cycle Characteristics

The measured stroke rates and intensities are similar to values previously reported (6). The experimental protocol required the rowers to combine stroke rates and intensities in ways they are not accustomed to. The results indicate that the participants had some difficulties with combining stroke rate and intensity in the non-self-chosen combinations. However, there was no overlap between measured stroke rate and intensity in the three instruction categories. Therefore, the participants' task execution is satisfactory for the purpose of this study. The exact findings could, on the other hand, have been somewhat different it the rowers had done a "perfect" job, and all stroke rates and intensities in one instruction category where exactly identical. Consequently, care should be taken in comparing values of conditions other than LL, MM and HH.

Results show that the rowers adjust their technique through manipulation of drive and recovery time, when either stroke rate or intensity increases. When stroke rate increases, both drive time and recovery time decreases. The reductions are, however, greatest in recovery time, which is reflected through an increase in relative drive time with increasing stroke rate. These results are in line with results reported by Hofmijster et al. (3). To the author's knowledge, the isolated effect of intensity on drive and recovery time have not been investigated previously. Results from the current study indicate that the rower adjust their technique in a different manner when they intend to increase intensity while keeping stroke rate constant; recovery time is not significantly affected, while drive time significantly decreases. Therefore, relative drive time decreases. This means that in order to produce a greater intensity, the rower shortens the drive time, i.e. moves faster during the drive, while keeping recovery time constant. This is somewhat supported by findings from Sprague et al. (27), who found that a higher intensity is achieved though faster movements of the rower during the drive, expressed by increasing handle velocity.

4.3 External Power

The present study found that that maximal body power significantly increased with intensity. The time profiles of body power at HH and LL were also significantly different from each other. Some of this is probably related to differences in amplitude: HH showed higher positive and lower negative peaks than LL. However, mechanical power of the body is small compared to joint power. Therefore, propulsion in rowing is primarily generated by the joints, in a direct manner. Considering that the rowers CoM mainly moves back and forth in a horizontal direction (28) this is logical, as the fluctuations in potential and kinetic energy and thus, body energy, will be small. This also makes it difficult for the rower to utilize power from the body in propulsion, as is possible in other sports such as cross-country double poling (29). Therefore, considerable part of body power in rowing can, possibly, be considered a loss.

An interesting finding is the similarities between the time profiles of body and seat power. The similarities suggest that an increase in body power implies increasing seat speed, and thus power. This might be related to the fact that movements of the seat to some extent can be used to approximate movements of the rowers' CoM (28). Martindale and Robertson (18) argued that there exists an exchange in energy between the boat and the rowers' body during the rowing cycle. Results from the current study suggests that this exchange does not occur through a direct transfer to the seat, and that the situation is complex. There is no clear mechanism that can transfer stopping of the body at the end of recovery into propulsive power (like bouncing and storage of elastic energy). However, the positive and then negative body power during the drive suggests that some of the body energy built up at the start of the drive might be used as propulsion in the second part of the drive.

4.4 Average and Relative Joint Power

The effect of both stroke rate and intensity on average joint power was found to be joint specific. In general, an increase in intensity was done by an even increase of power of all joints, except for the shoulder. However, also stroke rate affected power in some joints; the ankle, shoulder and elbow. The effect of stroke rate was opposite for ankle power and shoulder and elbow power; ankle power decreased, while shoulder and elbow increased with increasing stroke rate. This might be related to differences in muscular properties which favours power production of the shoulder and elbow at faster movements. Moreover, it might also be related to technical and coordinative adaptations made by the rower, in order to maintain intensity while increasing stroke rate. This, however, requires analysis of additional data, such as electromyography.

Results regarding relative joint power were also joint specific. In general, the effect of stroke rate was greater than the effect of intensity on relative joint power, seeing as stroke rate had a significant effect on all joints with the exception of hip joint power. This suggest that the rowers adjusted their technique by "rearranging" the contribution from individual joints when stroke rate increases. Results showed that the relative contribution from the upper limbs decrease with stroke rate at low intensity and increase with stroke rate at high intensity. Attenborough et al. (15) found that as stroke rate increased, the relative contribution from the upper limbs decreased. They described that the participants were instructed to exert maximal effort, while keeping the instructed stroke rate. However, values for intensity were not reported, which complicates comparisons with the present study. The current study found that the hip joint produced the greatest average and relative power across stroke rates and intensities. This is in line with results from Greene et al. (13), who found that the hip produces the greatest amount of energy. However, they studied only one stroke rate (32 strokes$\cdot$min^{-1}) and they reported total energy production from each joint. Therefore, the exact values and results are not directly comparable. On the other hand, it confirms that the results from the current study adds to the notion that the lower limbs, and especially the hips, are of great significance in propulsion in rowing (12).

Results regarding knee joint power show that on average, the knee joint power is negative. Negative power implies absorption of energy through eccentric contractions, or transfer of energy to other joints (30). The knee joint extends rapidly throughout the drive, which is the phase were the joint power is negative. If knee extension is generated by concentric muscle activity, (negative) knee joint power is most likely transferred to another joint. From Figure 9 it is evident that the positive peak in hip joint power occurs at approximately the same time as the negative peak in knee joint power. This suggests that power generated at the knee is transferred to the hip, and thereby occurs as hip joint power. This would also explain the high average and relative hip power values. The transfer of power between joints are made possible by bi-articular muscles crossing both the hip and knee joint (31). However, only looking at isolated joint powers, without considering inter-joint coordination, might lead to erroneous conclusions about which muscles are involved in power production. The existence, and moreover requirement, of this transfer of power is further supported through the previously described conflict between the observed moments of the task. Rowing seems to require a net knee extending moment, while the direction of the external force require a net knee flexing moment. Due to this, the bi-articular muscles in the lower limbs will likely transfer power between the joints, while the mono-articular muscles produce power. The existence of such a mechanism in rowing is supported by Wilson et al. (32), who investigated muscle function of the lower limbs in ergometer rowing. However, further analysis including both joint power and electromyography is necessary.

4.5 Time Profiles

A few previous studies have reported results on time profiles of joint power in rowing, for both upper (15) and lower limbs (13, 14, 16). However, this is to the author's knowledge the first study to statistically compare the time profiles of these joint powers. All joint powers displayed periods of significant difference during the drive phase. Considering the differences occurred at approximately the same time during the cycle as the positive and/or negative peaks in joint power, these differences are logically related to amplitude, but possibly also timing. However, this differentiation requires further and more thorough examination, which is outside the scope of this study that first and most is aimed at comparing contribution of joints depending on stroke rate and intensity.

The observed differences during recovery are also interesting. All joints except the ankle showed significant differences in joint power during recovery. Hofmijster et al. (17) argued that the acceleration of the rowers CoM during recovery should be kept low, considering it will reduce average velocity. Baudouin and Hawkins (11), as well as Sanderson and Martindale (8), emphasized the importance of understanding recovery kinematics and its possible effects on velocity of the boat. Results from this study indicate that both joint and body power is produced during recovery, and that the magnitude of power produced during recovery increased from LL to HH. The mechanism that allows much of this power during the recovery to be re-utilised during the drive is difficult to envisage. Therefore, this power can be considered a loss. However, some of the increase in power is probably a necessary investment in order to increase stroke rate. Considering recovery time decreased with increasing stroke rate, the rower has to move faster during recovery to return to the initial catch position. Determining to what extent the power produced during recovery effects performance, and average velocity, is of course an interesting line of future research.

4.6 Comparison of LL, MM and HH

The comparison of the self-chosen conditions LL, MM and HH showed that both stroke rate and power output significantly increased from LL to MM and HH. This is in line with previously reported results (e.g. ref. (5)). Almost all average joint powers significantly increased from LL to HH. This is logical, considering power output increased. Shoulder joint power, however, did not change from LL to MM and HH. This suggest that the shoulder power is somewhat constant and irrespective of an increase in stroke rate and power output. However, the result might also be related to the great inter-subject variation in shoulder joint power. The results that neither average nor relative shoulder joint power significantly changes from LL to MM and HH seems like a contradiction. However, this is possibly because some changes do occur, but they are not statistically significant. In terms of average joint power, rowing at LL and MM are more similar to each other. However, LL and MM show the same differences and similarities when compared to HH. Results regarding relative joint power showed there were no significant differences between the three conditions. Together, the results suggest that the coordination of the segments and joints while rowing at low intensity and stroke rate closely replicates rowing at moderate and high intensity and stroke rate. This means that it is possible to train competition-specific technique at low or moderate stroke rate and intensity.

4.7 Methodological Considerations

4.7.1 Trunk Power

In the present study, the trunk was modelled as one, stiff segment, which might be an oversimplification in rowing. McGregor and colleagues (33) found that there is substantial movement in both the lumbar and thoracic spine during ergometer rowing, and that these movements are altered by stroke rate. To what extent the movements in the trunk contribute to propulsion is not known. However, it has been argued that keeping the trunk stiff is essential in transferring stretcher power to the handle (12). Therefore, one can assume that the trunk is more important in transferring power than in generating power during the drive. As such, the assumption made modelling the trunk as one segment is considered sufficient for the purpose of this study, which was to reveal stroke rate and intensity effects of the contributions of joint powers. In the current analysis any power from joints of the trunk is attributed to hip and shoulder.

4.7.2 Practical Considerations Regarding Ergometer Versus Boat

Some considerations regarding the use of ergometer in this study should be discussed. A dynamic ergometer (RP3) was used in this study. First of all, the advantage of using an ergometer instead of a boat in research is that it reduces the possible, and likely, effect of external factors such as weather-conditions. Using an ergometer will therefore increase both the reliability and validity of the measurements. Lamb (34) found that rowing on a dynamic ergometer to a great extent replicates the movements of the lower limbs during on-water rowing. However, the movements of the upper limbs were not similar during ergometer and on-water rowing. On the other hand, Fleming et al. (35) argued that significant differences exists in kinematic patterns when comparing on-water and ergometer rowing. Consequently, care should be taken in generalizing the results from this study to on-water rowing. Still, there is no clear reason that would suggest that the main findings of this study would be different for on-water rowing.

4.8 Practical Implications and Further Research

The present study has provided additional understanding and knowledge of the underlying mechanisms of the rowing cycle. Being the first study to report average and relative values for joint powers of both lower and upper limbs, as well as how these change with stroke rate and intensity, the results are potentially valuable for both researchers and coaches. Several areas of interest for further research have been detected in this study, including analysis of time profiles, recovery kinematics and detailed analysis of individual joint powers. This study does not take into account the effect of increasing stroke rate and intensity on physiological aspects and efficiency. This could be a potential interesting field for future research. For coaches, the knowledge of both how the different joints contribute in propulsion and how well the technique at low, moderate and high intensity corresponds is of importance. It can help them in assessing possible mechanisms behind less effective or faulty technique. Furthermore, it is of relevance in training, because it provides knowledge on how race-specific technique-training at lower intensities is.

5. Conclusion

Increasing stroke rate and intensity show significant effects on average and relative joint power, as well as body power. The effects are joint specific. However, the effects seem to be cancelled out when comparing LL and HH, which are the conditions of main interest. The comparison of the time profiles of HH and LL revealed that the distribution of joint powers is similar during some parts of the cycle, but significant differences occurred both during the drive and recovery. The results suggest that the timing of joint powers might be affected as well. In general, rowing at low stroke rate and intensity is a similar motion as rowing at high stroke rate and intensity, but with subtle differences.

6. References

1. Ingham SA, Whyte GP, Jones K, Nevill AM. Determinants of 2,000 m rowing ergometer performance in elite rowers. European journal of applied physiology. 2002;88(3):243-6.

2. Kleshnev V. An analysis of the results of the 2018 World Rowing Championships [Internet]. Biorow.com 2018 [retrieved 01.05.2020]. Available from: http://biorow.com/index.php?route=information/news/news&news_id=38

3. Hofmijster MJ, Van Soest AJ, De Koning JJ. Gross efficiency during rowing is not affected by stroke rate. Medicine and science in sports and exercise. 2009;41(5):1088-95.

4. Steinacker JM. Physiological aspects of training in rowing. Int J Sports Med. 1993;14 Suppl 1:S3-10.

5. Soper C, Hume PA. Towards an ideal rowing technique for performance: the contributions from biomechanics. Sports medicine (Auckland, NZ). 2004;34(12):825-48.

6. Hofmijster MJ, Landman EH, Smith RM, Van Soest AJ. Effect of stroke rate on the distribution of net mechanical power in rowing. J Sports Sci. 2007;25(4):403-11.

7. Bourdin M, Messonnier L, Hager JP, Lacour J-R. Peak Power Output Predicts Rowing Ergometer Performance in Elite Male Rowers. International journal of sports medicine. 2004;25:368-73.

8. Sanderson B, Martindale W. Towards optimizing rowing technique. Medicine & Science in Sports & Exercise. 1986;18(4).

9. van der Kruk E, van der Helm FCT, Veeger HEJ, Schwab AL. Power in sports: A literature review on the application, assumptions, and terminology of mechanical power in sport research. J Biomech. 2018;79:1-14.

10. Smith RM, Spinks WL. Discriminant analysis of biomechanical differences between novice, good and elite rowers. Journal of Sports Sciences. 1995;13(5):377-85.

11. Baudouin A, Hawkins D. A biomechanical review of factors affecting rowing performance. British journal of sports medicine. 2002;36(6):396-402; discussion

12. Buckeridge EM, Bull AM, McGregor AH. Biomechanical determinants of elite rowing technique and performance. Scand J Med Sci Sports. 2015;25(2):e176-83.

13. Greene AJ, Sinclair PJ, Dickson MH, Colloud F, Smith RM. The effect of ergometer design on rowing stroke mechanics. Scandinavian Journal of Medicine & Science in Sports. 2013;23(4):468-77.

14. Greene AJ, Sinclair PJ, Dickson MH, Colloud F, Smith RM. Relative shank to thigh length is associated with different mechanisms of power production during elite male ergometer rowing. Sports Biomech. 2009;8(4):302-17.

15. Attenborough AS, Smith RM, Sinclair PJ. Effect of gender and stroke rate on joint power characteristics of the upper extremity during simulated rowing. Journal of Sports Sciences. 2012;30(5):449-58.

16. Kyrolainen H, Smith R. Mechanical power output and muscle activities during maximal rowing with different stroke rates. Journal of Human Movement Studies. 1999;36:75-94.

17. Hofmijster MJ, Van Soest AJ, J. DKJ. Rowing skill affects power loss on a modified rowing ergometer. Medicine and science in sports and exercise. 2008;40(6):1101-10.

18. Martindale W, Robertson D. Mechanical energy in sculling and in rowing an ergometer. Canadian journal of applied sport sciences. 1984;9:153-63.

19. Kleshnev V. Estimation of Biomechanical Parameters and Propulsive Efficiency of Rowing Australian Institute of Sport, Biomechanics dept 1998:1-17.

20. Warmenhoven J, Cobley S, Draper C, Smith R. Over 50 Years of Researching Force Profiles in Rowing: What Do We Know? Sports medicine (Auckland, NZ). 2018;48(12):2703-14.

21. Hofmijster MJ, Lintmeijer LL, Beek PJ, van Soest AJK. Mechanical power output in rowing should not be determined from oar forces and oar motion alone. Journal of Sports Sciences. 2018;36(18):2147-53.

22. deLeva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech. 1996;29(9):1223-30.

23. Elftman H. Forces and energy changes in the leg during walking. American Journal of Physiology-Legacy Content. 1939;125(2):339-56.

24. Haugen T, McGhie D, Ettema G. Sprint running: from fundamental mechanics to practice—a review. European journal of applied physiology. 2019;119(6):1273-87.

25. Friston K, Ashburner J, Kiebel S, Nichols T, Penny W. Statistical Parametric Mapping. London: Academic Press; 2007 2007/01/01/. 656 p.

26. Bland M. An Introduction to Medical Statistics. 4 ed. Oxford: Oxford University Press; 2015.

27. Sprague RC, Martin JC, Davidson CJ, Farrar RP. Force-velocity and power-velocity relationships during maximal short-term rowing ergometry. Medicine and science in sports and exercise. 2007;39(2):358-64.

28. Lintmeijer LL, Faber GS, Kruk HR, van Soest AJK, Hofmijster MJ. An accurate estimation of the horizontal acceleration of a rower's centre of mass using inertial sensors: a validation. Eur J Sport Sci. 2018;18(7):940-6.

29. Danielsen J, Sandbakk Ø, Holmberg HC, Ettema G. Mechanical Energy and Propulsion in Ergometer Double Poling by Cross-country Skiers. Medicine and science in sports and exercise. 2015;47(12):2586-94.

30. Winter DA. Biomechanics and Motor Control of Human Movement 4ed. Ontario, Canada: John Wiley & Sons, Inc. ; 2009.

31. Van Ingen Schenau GJ. From rotation to translation: Constraints on multi-joint movements and the unique action of bi-articular muscles. Human Movement Science. 1989;8(4):301-37.

32. Wilson JM, Robertson D, Stothart P. Analysis of lower limb muscle function in ergometer rowing. Journal of Applied Biomechanics. 1988;4:315-25.

33. McGregor AH, Bull AM, Byng-Maddick R. A comparison of rowing technique at different stroke rates: a description of sequencing, force production and kinematics. Int J Sports Med. 2004;25(6):465-70.

34. Lamb DH. A kinematic comparison of ergometer and on-water rowing. Am J Sports Med. 1989;17(3):367-73.

35. Fleming N, Donne B, Mahony N. A comparison of electromyography and stroke kinematics during ergometer and on-water rowing. J Sports Sci. 2014;32(12):1127-38.

NTNU

Norwegian University of
Science and Technology