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Different inertial properties between static and dynamic rowing ergometers cause acute adaptations in coordination patterns

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Abstract: With ergometers being frequently used in training programmes of rowers, consensus is needed to identify which design most closely reproduces the biomechanics of on-water rowing. Discussion exists about the movement allowed to the stretcher, with static designs fixating it, while dynamic models allowing displacement. To investigate how this affects muscular and kinematic coordination patterns, a group of nine male rowers were analysed whilst exercising on three ergometer designs, a static ergometer and two dynamic versions. 3D motion analysis was applied to measure displacement of body segments, joint angles and angular velocities. Electromyography was used to record activation patterns of major muscles. All participants were measured on all three ergometer designs; data were analysed using repeated measures ANOVA. Duration of the stroke phase turned out to be longer on the static ergometer and tibialis anterior and biceps femoris coordination patterns differed between static and dynamic ergometers. Kinematic data showed a more squatted posture at the end of recovery on the static ergometer. These differences were interpreted as distorted movement coordination resulting from the more inert moving mass on the static ergometer.

Nils Jongerius, Paul B.J. Willems and Hans H.C.M. Savelberg

ABOUT THE AUTHORS

The biomechanical work of our research group concentrates on unravelling the impact of impairments or interventions in human movement on coordination of movement and the subsequent performance. Understanding of the impact of impairments on movement execution and final movement performance helps to design and optimize interventions, i.e. reconditioning programmes or aides, and to overcome or compensate a reduced capacity. Applied to sports, this approach contributes to better understand performance limiting factors and optimise training programmes.

PUBLIC INTEREST STATEMENT

Rowers use rowing machines when on-water rowing is not possible. Therefore, for rowers, these machines should contribute to improve rowing technique and coordination. Rowing machines come in two designs. Static rowing machines, those most frequently seen in gyms, have a static flywheel, requiring the athlete to move on the seat. Contrarily, dynamic machines have a moving flywheel, allowing the rower to stay still. This study showed the difference in mass (static: rower's body; dynamic: flywheel) being displaced on both types of machines to influence coordination of the movement. On the static machine, effort to control the movement was higher due to the larger mass being accelerated and braked. This implies that a seemingly similar movement pattern is accomplished with different muscle activation patterns at dynamic versus static machines. Consequently, dynamic and static machines train different coordination patterns and cannot be used equally to train technique for on-water rowing.

Subjects: Fitness and Training; Kinesiology; Sports Performance Analysis; Biomechanics and Human Movement Science

Keywords: muscle activation; kinematics; rowing ergometer; inertial properties; electromyography; angular velocity

1. Introduction

When rowers cannot train on-water, ergometers are an alternative. Therefore, ergometers should provide opportunity to train performance capacity and to develop technical skills. A dispute in ergometer design is whether the stretcher should move. A commonly used design is the air-braked Concept2 ergometer with a fixed flywheel and stretcher. When a rower extends their legs, the flywheel and stretcher do not move and the seat with the rower's trunk accelerates backwardly. During on-water rowing, pushing against a fixed base is not possible. To better mimic on-water rowing, dynamic ergometers were designed. The moving flywheel and stretcher of dynamic ergometers simulate the non-fixed base of the boat.

Previous studies comparing ergometer designs found higher power output and larger external and internal forces on static dynamometers (Bernstein, Webber, & Woledge, 2002; Colloud, Bahuaud, Doriot, Champely, & Chèze, 2006). These authors suggested that consequently static ergometers bear a higher injury risk. Greene, Sinclair, Dickson Colloud, and Smith (2013) reported increased mechanical efficiency on dynamic ergometers. A few studies comparing muscle activation and kinematics reported contrasting effects (Fleming, Donne, & Mahony, 2014; Nowicky, Burdett, & Horne, 2005). Such differences between ergometers affect development of technique and its transfer to on-water rowing.

A major difference between static and dynamic ergometers is the amount of mass moving while rowing. On the dynamic ergometer, the flywheel moves; the mass of the flywheel is considerably lower than the body mass of the rower that is displaced on the static ergometer. It should be appreciated that this inertial difference affects coordination patterns. On the static ergometer, a comparable kinematic pattern has to be generated by more muscle force than on the dynamic ergometer. Therefore, to adequately evaluate similarity in coordination patterns between both types of ergometers, it is important to simultaneously measure kinematic patterns (joint angles and joint angular velocity) and muscle activation profiles (timing, duration and level of activation). We hypothesize that non-similarity is related to differences in inertial properties between the ergometer designs. The present study compared coordination patterns for ergometer rowing on the static Concept2 (C2), on the Concept2 Dynamic (C2D) and on the dynamic RowPerfect3 (RP3).

2. Methods

2.1. Subjects

Nine male rowers (age 21.4 ± 0.7 years, mass 79.3 ± 9.2 kg, height 1.87 ± 0.10 m), training at least 5 times a week over the last 6 months participated. All participants had recently competed at national level. In line with the Declaration of Helsinki, participants provided informed consent prior to participating and had the freedom to withdraw from the study throughout data collection.

2.2. Measurements

The subjects rowed on the C2, C2D and RP3 in random order. Both dynamic ergometers were used to compare the effects of different moving flywheel designs. The mass of the flywheel and stretcher of the RP3 (17 kg) is considered to mimic that of single sculls. The C2D creates resistance by a pulley system attached to a flywheel, with only a stretcher moving. The inertial properties of this system have not been disclosed. Moreover, the RP3 works with a freely moving seat, whereas the C2D limits movement of the seat by elastic ropes. Following a 5-min familiarisation, subjects increased rowing pace to 20 strokes/minute at a stable (±3 beats/min) heart rate of 140–150 beats/min. At this intensity, five individual, i.e. non-sequential, strokes were recorded. After a 10-min rest, the protocol was successively repeated on the other ergometers. Continuously, participants received feedback on heartrate and stroke rate. Given the high level of the participants' performance capacity and their familiarity to this kind of exercise bouts, the risk of participating in this study was low. Yet, a medical doctor supervised the execution of the experiments.

Surface electromyography (EMG) recorded activation of key lower extremity muscles: gastrocnemius lateralis (GL), tibialis anterior (TA), rectus femoris (RF), vastus lateralis (VL) and biceps femoris (BF). Concurrently, an optoelectronic motion-capture system recorded kinematic data for which participants were prepared according to the Vicon Plug-in-gait model. Hand and head markers were omitted as these disturbed accurate recording of more essential markers.

2.3. Data analysis

All data were anonymized. Raw EMG signals were processed using a bandpass filter (order: 4 Hz: 10–200) and a percentage filter (50%, window: 0.3 s), followed by calculating the root mean square (window: 0.1 s). Per individual, muscle activation signals were normalised to the maximal value measured at any of the three machines.

Kinematic and muscle activation data were normalised for both stroke and recovery phase separately. Transition between both phases was based on the extreme, horizontal position of the elbow. Data were analysed using a 0–200% range (1–100% stroke phase; 101–200% recovery phase).

Muscles were considered active when exceeding a threshold equal to a percentage of maximal activation for a minimal duration of 5% of either stroke or recovery phase. For each muscle, a specific threshold was chosen visually as to optimally cope with signal/noise ratios (Table 1).

Onset, offset and normalised EMG peak values were quantified as well as the timing of these peaks in percentages of the rowing cycle. For kinematic data, extremes of joint angles, their velocities and timing of extremes were defined.

Repeated measures ANOVA with an α set at 0.05 was applied to statistically test differences between the ergometers. Bonferonni correction was applied for pairwise comparison of ergometers. Excessive noise on some data caused N to be reduced to 7 for the hip, pelvis, VL, RF, GL and BF data, and to $N = 5$ for TA data.

3. Results

3.1. Stroke duration and timing

In accordance with the study design, average duration of a cycle did not differ between the ergometers ($p = 0.117$). However, on the C2, the stroke/recovery ratio was significantly larger than on both the C2D and RP3 (0.60 ± 0.05 vs. 0.51 ± 0.03; $p < 0.001$ and 0.52 ± 0.05; $p = 0.026$, respectively). These different ratios were caused by the stroke lasting ~15% longer on the C2 ($p = 0.001$; Table 2) than on both dynamic ergometers. Recovery duration remained unaffected.

Table 1. Activation threshold as a percentage of maximal activation

	TA	RF	VL	GL	BF
Threshold (%)	20	17.5	20	20	17.5

GL: Gastrocnemius lateralis; TA: tibialis anterior; RF: rectus femoris; VL: vastus lateralis; BF: biceps femoris.

Table 2. Temporal stroke and recovery characteristics

	Cycle duration (s)	Stroke duration (s)	Recovery duration (s)	Stroke/Recovery ratio
C2	3.11 (0.11)	1.16 (0.05)#*1	1.95 (0.11)	0.60 (0.05)#*1
C2D	3.10 (0.17)	1.04 (0.04)#	2.06 (0.14)	0.51 (0.03)#
RP3	2.96 (0.21)	1.00 (0.04)#	1.95 (0.20)	0.52 (0.05)#

#Significant differences ($p < 0.05$).
*Significantly different from C2D ($p < 0.05$).
1Significantly different from RP3 ($p < 0.05$).
C2: Concept2 (C2); C2D: Concept2 Dynamic; RP3: RowPerfect3.

3.2. Muscle activation

Maximal VL activation was significantly affected by ergometer design ($p = 0.042$; Figure 1c). Maximal activation of the other muscles did not differ. Timing of maximal activation of TA and BF differed between ergometers (Figure 1a and 1e). Maximal TA activation occurred significantly earlier ($p = 0.042$) on the C2 (86% of recovery) than on both dynamic ergometers (RP3: 93%; C2D: 96%; Table 3). Also, TA onset occurred earlier on the C2 ($p = 0.036$; C2: 60% of recovery, C2D: 77% and RP3: 71%). Maximal BF activation was retarded on the C2 ($p = 0.029$); it occurred at 35% of the stroke, compared to 24% (RP3) and 27% (C2D). In addition to this, BF activation started later on the C2 ($p = 0.001$; 15% of stroke) compared to C2D (91% of recovery) and RP3 (89% of recovery). BF activation showed a significantly shorter duration on the C2 ($p < 0.001$, 20% of the total cycle) than on C2D (33%) and RP3 (34%). RF activation terminated later on C2D than on RP3 (30% vs. 15% of recovery, $p = 0.026$). Temporal characteristics of VL were not affected by the ergometer type.

3.3. Joint angles and angular velocity

Maximal ankle dorsal flexion was about 4° larger on the C2 than on both dynamic ergometers ($p = 0.002$; Table 4). Maximal plantar flexion was 3–5° larger on the RP3 than on both Concept2 ergometers ($p < 0.001$; Table 4). Consequently, ankle range of movement was smallest on the C2D ($p = 0.002$). Maximal plantar flexion velocity was significantly higher (~20°/s) on the C2 ($p < 0.001$; Table 5) than on both dynamic ergometers. The maximal dorsal flexion velocity did not differ; on the C2D, the maximal velocity was reached later in the recovery.

On the C2D, maximal knee joint flexion was approximately 5° less than on RP3 ($p = 0.018$) and about 9° less than on the C2 ($p = 0.030$). Also, timing of the maximal flexion differed significantly; on the C2D, maximal flexion was reached 1% after starting the stroke; on the C2 and R3P, it occurred 1.5% before finishing recovery ($p = 0.003$). Maximal knee joint extension was not affected. The smaller knee joint flexion angle contributed to an 8° smaller range of motion on the C2D compared to the RP3 ($p = 0.018$). Maximal extension and flexion velocity were both not affected.

On the RP3, maximal hip extension was reached 9% earlier than on the C2D ($p = 0.023$). The maximal extension velocity of the hip joint was ~13% lower on both dynamic ergometers than on the C2 (Table 5; C2 vs. C2D $p = 0.039$; C2 vs. RP3 $p = 0.015$). During the recovery phase, the maximal flexion velocity on the C2D occurred about 10% later than on both other ergometers. Maximal and minimal hip joint angles were not different.

On C2, the maximal backward tilting velocity, which occurs during the stroke phase, was ~15°/s higher than on both dynamic ergometers ($p = 0.024$). During the recovery, the maximal forward tilting velocity of the pelvis occurred 10–15% later on the C2D compared to the C2 and RP3 ($p = 0.006$). Maximal forward and backward orientation were not affected.

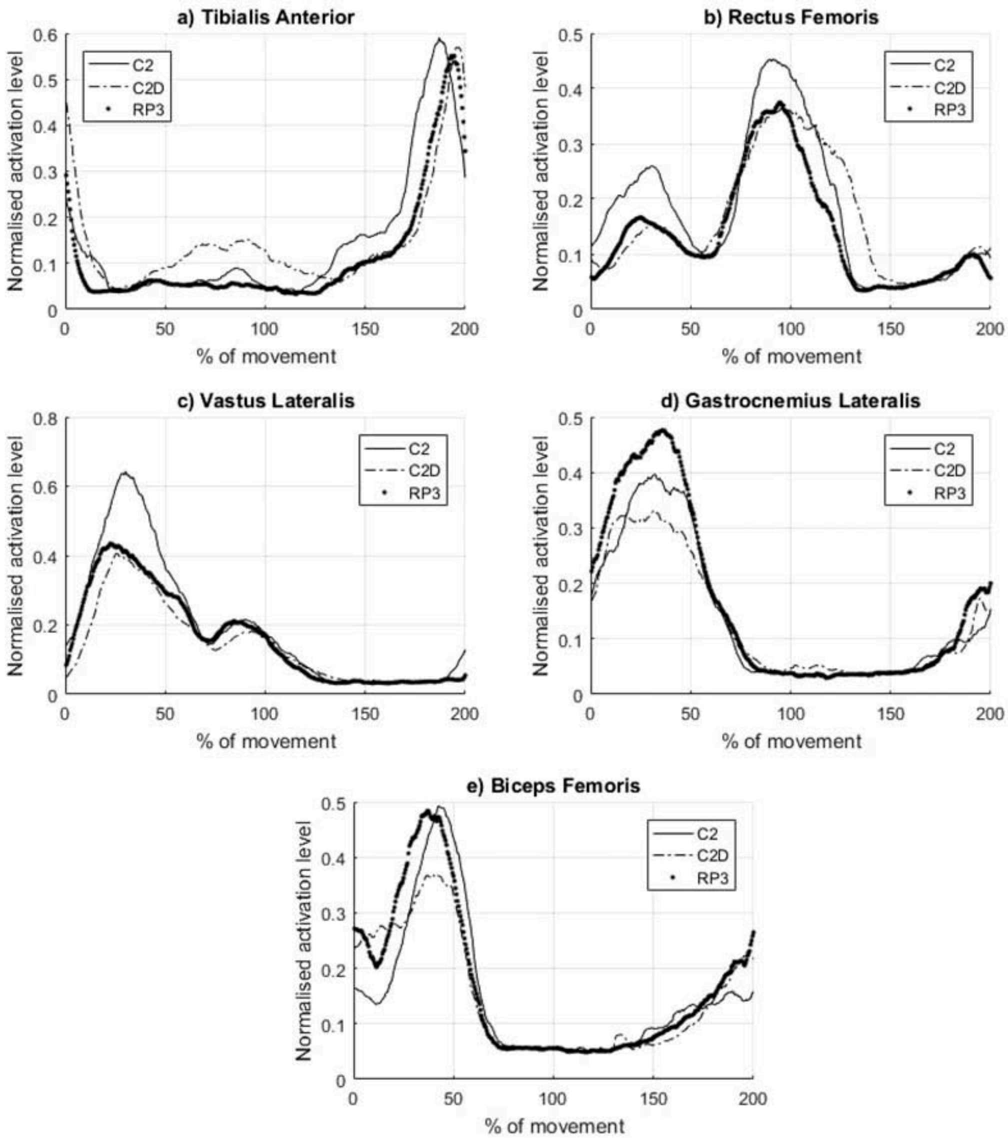

Figure 1. Muscle activation of tibialis anterior, rectus femoris, vastus lateralis, gastrocnemius lateralis and biceps femoris (1a–e). Solid lines represent C2 activation, dashed lines C2D and dotted lines RP3. Activation patterns were normalised to the maximal value reached and shown as a function of normalised rowing cycle, 0–100% represents the stroke, 101–200% the recovery.

4. Discussion

In evaluating similarity in coordination patterns, this study showed differences between rowing ergometer designs. The study revealed different stroke/recovery ratios between ergometers. On both dynamic ergometers, recovery lasted twice as long as the stroke, resulting in a ratio of ~0.50, this increased to ~0.60 on the static ergometer. Albeit of different magnitude, this is in line with literature. Fleming et al. (2014) reported ratios of 0.33–0.35 for dynamic and static ergometers, respectively. In contrast, Benson, Abendroth, King and Swensen (2011) reported values of 0.48 (static) and 0.54 (dynamic) when rowing at 28–30 strokes/min. Such stroke rate difference might explain the different directions of the effect. None of these previous studies analysed whether these changes of intracycle timing affected kinematics and coordination patterns.

At the beginning of the stroke phase (i.e. the “catch”), the participants took a more squatted position on the static C2 compared to both dynamic ergometers. On the C2, ankle dorsal flexion and knee flexion were more pronounced. Subsequently, during the stroke, participants reached higher plantar flexion, knee joint extension, hip extension and backward pelvis rotation velocities at the C2 compared to both

Table 3. Muscle activation characteristics

		Maximal activation (%)	Maximal activation timing	Onset	Offset	Duration
Tibialis anterior	**C2**	63.8 (12.5)	168.4 (4.8)[#*]	160.3 (13.6)[#]	6.3 (9.3)	45.8 (20.8)
	C2D	61.2 (17.3)	195.8 (3.1)[#]	177.0 (11.8)[#]	6.0 (7.0)	28.8 (17.6)
	RP3	58.7 (12.3)	192.8 (3.1)[#]	171.3 (9.9)[#]	0.3 (0.3)	29.1 (9.9)
Rectus femoris	**C2**	52.5 (13.6)	93.7 (11.4)	71.6 (6.6)	122.1 (5.8)[#]	50.4 (8.1)[#]
	C2D	42.7 (10.3)	98.3 (15.7)	72.0 (9.7)	130.1 (10.1)[#1]	58.1 (18.0)[#]
	RP3	41.1 (13.1)	72.0 (9.7)	72.1 (10.5)	115.6 (10.2)[#]	43.6 (17.3)[#]
Vastus lateralis	**C2**	68.3 (10.6)[#]	34.9 (10.1)	6.2 (5.5)[#]	67.2 (21.5)	61.0 (23.9)
	C2D	48.0 (13.8)[#]	33.3 (14.2)	16.0 (9.0)[#]	61.3 (9.4)	45.4 (16.9)
	RP3	51.6 (19.7)[#]	31.3 (14.8)	9.2 (8.5)[#]	57.6 (10.7)	48.4 (16.9)
Gastrocnemius lateralis	**C2**	47.7 (13.4)	26.9 (12.7)	3.9 (8.9)	55.9 (12.8)	52.1 (15.3)
	C2D	46.1 (12.2)	29.1 (19.9)	0.5 (9.2)	49.5 (20.8)	48.9 (18.4)
	RP3	56.5 (14.8)	28.3 (10.9)	193.2 (8.1)	56.3 (16.5)	62.9 (21.4)
Biceps Femoris	**C2**	48.9 (14.2)	35.6 (15.0)[#]	14.8 (11.3)[#*1]	53.8 (18.7)	38.9 (10.3)[#*1]
	C2D	48.2 (13.2)	28.9 (17.0)[#]	190.6 (18.8)[#]	15.8 (3.8)	66.1 (18.9)[#]
	RP3	58.0 (16.4)	24.1 (19.2)[#]	189.1 (19.2)[#]	56.8 (6.0)	67.5 (17.4)[#]

[#]Significant differences ($p < 0.05$).
*Significantly different from C2D ($p < 0.05$).
[1]Significantly different from RP3 ($p < 0.05$).
C2: Concept2 (C2); C2D: Concept2 Dynamic; RP3: RowPerfect3.

Table 4. Joint angle extremes and timing

		Maximal flexion (°)	Maximal flexion timing (%)	Minimal flexion (°)	Minimal flexion timing (%)	Range of motion (°)
Ankle[§]	**C2**	45.7 (9.6)[#*1]	199.4 (4.2)	22.7 (6.8)[#1]	103.5 (15.6)	68.4 (9.0)[#*]
	C2D	42.0 (8.9)[#]	2.0 (2.5)	20.7 (5.4)[#1]	105.9 (21.3)	62.7 (9.6)[#1]
	RP3	41.7 (8.5)[#]	199.6 (1.3)	25.7 (6.8)[#]	97.9 (15.4)	67.4 (8.8)[#]
Knee	**C2**	133.2 (7.3)[#*]	198.6 (1.1)[#*]	11.5 (5.5)[#]	98.6 (20.5)	121.8 (6.3)[#]
	C2D	124.3 (9.8)[#1]	200.9 (2.2)[#1]	11.7 (5.9)[#]	97.7 (19.6)	112.6 (11.1)[#1]
	RP3	129.8 (9.2)[#]	198.2 (1.4)[#]	9.1 (6.1)[#]	89.6 (13.9)	120.7 (10.0)[#]
Hip	**C2**	105.2 (10.5)	197.3 (3.9)[#]	30.7 (8.4)	96.8 (7.2)[#]	74.5 (12.4)
	C2D	103.9 (12.4)	0.9 (2.2)[#]	32.7 (6.8)	102.6 (5.7)[#1]	71.2 (12.2)
	RP3	103.7 (12.3)	198.9 (2.1)[#]	32.3 (6.8)	93.7 (9.0)[#]	71.4 (12.6)
Pelvic tilt[§]	**C2**	12.3 (12.2)	188.8 (24.1)	50.2 (8.1)	99.9 (2.7)[#]	37.9 (13.8)
	C2D	14.4 (14.2)	192.8 (13.6)	50.2 (6.2)	105.9 (7.6)[#1]	35.8 (12.4)
	RP3	14.8 (13.8)	185.7 (19.4)	49.2 (5.7)	98.4 (6.3)[#]	34.4 (12.3)

[#]Significant differences ($p < 0.05$).
*Significantly different from C2D ($p < 0.05$).
[1]Significantly different from RP3 ($p < 0.05$).
[§]Flexion reflects dorsal flexion at the ankle and forward tilt in the pelvis.
C2: Concept2 (C2); C2D: Concept2 Dynamic; RP3: RowPerfect3.

dynamic ergometers. This resulted in similar postures at the end of the stroke as only a small increase in plantar flexion angle occurred for the RP3. With the exception of pelvic rotation, maximal angular velocities were comparable over the ergometers during the recovery. In contrast, Nowicky et al. (2005)

Table 5. Joint angular velocity extremes and timing

		Maximal flexion velocity (°/s)	Maximal flexion velocity timing (°/s)	Maximal extension velocity (°/s)	Maximal extension velocity timing (%)
Ankle§	**C2**	140.0 (22.1)	156.8 (12.4)#*	141.2 (21.1)#*1	43.7 (6.6)
	C2D	142.4 (30.2)	169.0 (11.3)#	120.8 (18.8)#	46.2 (8.1)
	RP3	133.3 (22.9)	159.6 (11.5)#	117.9 (14.4)#	41.6 (13.6)
Knee	**C2**	228.1 (28.4)	154.5 (16.0)	217.0 (22.1)#*	48.3 (10.6)
	C2D	234.1 (44.3)	165.9 (15.9)	198.0 (24.0)#	48.8 (13.6)
	RP3	224.1 (30.5)	161.8 (18.3)	202.7 (15.8)#	19.8 (15.2)
Hip	**C2**	159.7 (34.5)	136.3 (5.1)#*	155.7 (28.4)#*1	57.4 (8.6)
	C2D	152.6 (36.7)	149.6 (7.7)#1	133.3 (28.8)#	54.6 (6.2)
	RP3	140.4 (37.3)	139.8 (7.0)#	134.4 (29.7)#	50.4 (5.6)
Pelvic tilt§	**C2**	97.4 (38.4)	127.8 (5.9)#*	79.7 (23.5)#*1	61.0 (10.7)#
	C2D	86.5 (34.0)	142.7 (12.6)#1	63.0 (22.4)#	52.9 (13.4)#
	RP3	83.7 (29.7)	131.6 (8.2)#	64.0 (22.3)#	48.0 (8.9)#

#Significant differences ($p < 0.05$).
*Significantly different from C2D ($p < 0.05$).
1Significantly different from RP3 ($p < 0.05$).
§Flexion reflects dorsal flexion at the ankle and forward tilt in the pelvis.
C2: Concept2 (C2); C2D: Concept2 Dynamic; RP3: RowPerfect3.

found no adaptations in range of motion of hip and knee joints. They did not incorporate changes in joint angular velocity.

Ergometer design affected VL, BF and TA activation. On the static ergometer, VL was more active and BF was delayed. TA activation in the recovery was slightly earlier. Nowicky et al. (2005) did not find intensity differences; their approach was not sensitive enough to compare timing. Fleming et al. (2014) found larger VM activation at the static ergometer similar to the reported VL amplitudes.

The more tucked posture around the catch on the C2 suggests that the athletes had problems braking and controlling the movement on the static ergometer. At the end of the recovery phase, flexion of the leg must be decelerated and transformed into extension. Kinematic data showed similarity in flexion velocities but differences between ergometers with respect to the decelerating mass. With the static ergometer, the mass to be decelerated is the rower's mass. With both dynamic ergometers, the mass to be decelerated is the considerably lower mass of the stretcher and the flywheel, 17 kg for RP3 or the unknown, elastic force generated by the pulling cord for C2D. This implies a higher required impulse during the catch at C2. Thus, it can be understood that recovery during static ergometry ends in a more squatted posture. Given the imposed cycle duration, a faster movement must be generated when using the C2 during the stroke, implying higher angular velocities.

Earlier VL activation and an increased maximal amplitude on the C2 are consistent with the more challenged control around the catch. The earlier activation agrees with the increased challenge to brake the forward movement around the catch.

Phase diagrams, plotting angles versus angular velocities, are most illustrative to visualise adaptations in coordination (Figure 2). Figure 2a shows that during the stroke on the C2 plantar flexing velocity is increased at all ankle joint angles; Figure 2b and 2c illustrates similar adaptations for knee and hip, respectively.

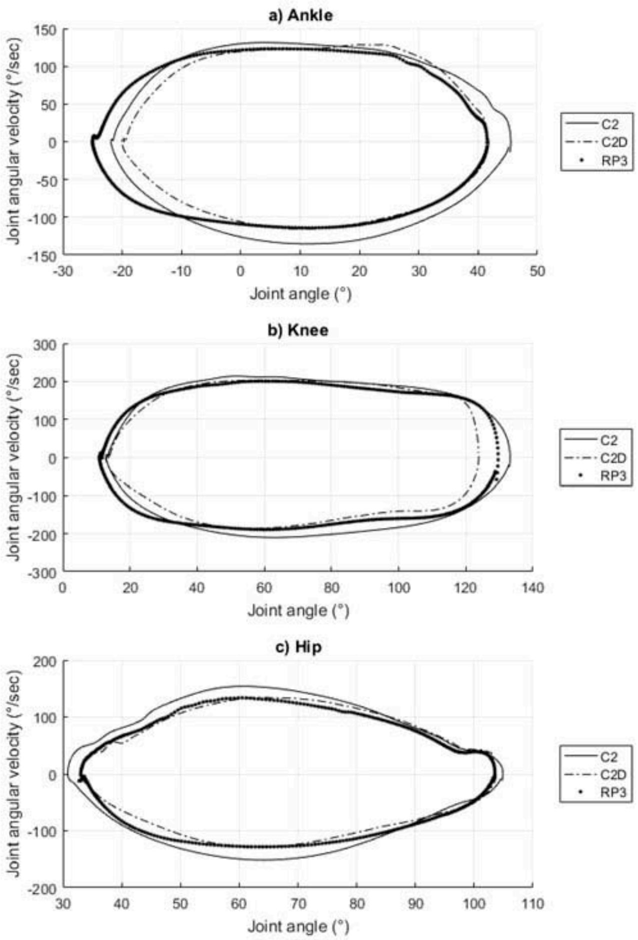

Figure 2. Joint angle versus angular velocity. The start of the rowing cycle at the catch occurs at "3 o'clock", the cycle proceeds in a clockwise direction. At "9 o'clock", the recovery phase starts.

This study suggests that the major difference between ergometer designs is in the increased challenge to control the inert body at the end of the recovery phase. Greene et al. (2013) came to a similar conclusion when comparing joint moments and mechanical energy in static and dynamic ergometers.

Although comparable to previous experiments, the number of subjects in this study is close to what is statistically acceptable. The significant results of the present study must be confirmed in a larger population. Only acute effects were measured in a population most familiar with the C2. Training studies should assess chronic effects of ergometer designs.

To better understand the intermuscular coordination resulting in adapted kinematic patterns of the leg segments, monitoring a wider range of mono- and bi-articular leg muscles would have been preferred. Additionally, it is advisable to include force measurements allowing inverse dynamic analysis in future studies. The final goal of comparing ergometer types is to discover which design prepares athletes best for on-water rowing. Having found considerably different coordination patterns between ergometer designs, on-water measurements are warranted as a next step.

In conclusion, this is one of few studies assessing differences in joint angles and angular velocities across static and dynamic ergometers. Additionally, monitoring muscle activation patterns found that different coordination patterns occur on static and dynamic ergometers. These differences become best visual around the catch and are suggested to result from differing inertial characteristics between ergometer designs.

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