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The impact of impairment on kinematic and kinetic variables in Va'a paddling: Towards a sport-specific evidence-based classification system for Para Va'a

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ABSTRACT
Para Va'a is a new Paralympic sport in which athletes with trunk and/or leg impairment compete over 200 m. The purpose of this study was to examine the impact of impairment on kinematic and kinetic variables during Va'a ergometer paddling. Ten able-bodied and 44 Para Va'a athletes with impairments affecting: trunk and legs (TL), legs bilaterally (BL) or leg unilaterally (UL) participated. Differences in stroke frequency, mean paddling force, and joint angles and correlation of the joint angles with paddling force were examined. Able-bodied demonstrated significantly greater paddling force as well as knee and ankle flexion ranges of movement (ROM) on the top hand paddling side compared to TL, BL and UL. Able-bodied, BL and UL demonstrated greater paddling force and trunk flexion compared to TL, and UL demonstrated larger bottom hand paddling side knee and ankle flexion ROM compared to BL. Significant positive correlations were observed for both male and female athletes between paddling force and all trunk flexion angles and ROM in the trunk and pelvis rotation and bottom hand paddling side hip, knee and ankle flexion. The results of this study are important for creating an evidence-based classification system for Para Va'a.

ARTICLE HISTORY
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KEYWORDS
Outrigger; paddling force; paralympics; disability

Introduction

Va'a paddling is a canoeing sport performed in a Polynesian outrigger canoe which is propelled by a single blade paddle on flat-water or open-water. In sprint Va'a, able-bodied athletes compete over 500, 1000 or 1500 m in a boat consisting of one athlete (V1) or in a crew boat consisting of six (V6) or 12 athletes (V12). In sprint Para Va'a, athletes with physical impairments compete over 200, 250, 500 or 1000 m in V1, V6 or V12. In 2017 the International Paralympic Committee (IPC) decided to include Para Va'a in the 2020 Paralympic Games in Tokyo. The events that will be contested are V1 200 m flat-water races. One of the conditions for inclusion was to comply with the IPC Athlete Classification Code by developing a sport-specific classification system through evidence-based research focusing on the relationship between impairment and key performance determinants (IPC, 2015). Tweedy, Mann, and Vanlandewijck (2016) highlighted six steps that are necessary for creating evidence-based classification systems. The International Canoe Federation (ICF) has already completed the first step which was to identify those eligible for the sport, which for Para Va'a includes persons with impaired passive ROM, impaired muscle power and limb deficiency affecting the trunk and legs. The second step, 'developing a theoretical model of the determinants of sports performance' (Tweedy et al., 2016), is, therefore, the subsequent step.

According to the available literature, the use of the legs and trunk in the outrigger technique varies among able-bodied athletes and paddling styles (Humphries, Abt, Stanton, & Sly, 2000). From an able-bodied perspective two common paddling styles have been described: using a greater trunk flexion/extension range of motion (ROM) and a longer stroke is termed "Hawaiian style", whereas having more trunk rotation and a shorter stroke is termed "Tahitian style" (Sealey, Ness, & Leicht, 2011). Furthermore, Sealey et al. (2011) showed that during 1000 m outrigger canoeing on an ergometer, experienced female outrigger canoeists adopted a shorter stroke with less trunk flexion movement at a higher stroke rate, whereas with a lower stroke rate, the athletes adopted a longer stroke and used a greater range of trunk flexion movement. Since each paddling style involves a combination of trunk flexion/extension and rotation, the trunk clearly plays an active role (Sealey et al., 2011). It is, however, unknown how an impairment affects this role. Although no known research has been conducted on Para Va'a, extensive research has been conducted on the role of the trunk in other Para sports. In wheelchair racing, for example, the trunk seems to have a role as a stable base for arms to push (Vanlandewijck, Verellen, Beckman, Connick, & Tweedy, 2011a; Vanlandewijck, Verellen, & Tweedy, 2011b). In cross-country sit-skiing the trunk seems to have a more active role leading to an increase of the propulsive force component (Gastaldi, Pastorelli, & Frassinelli, 2012; Rosso et al., 2019) and in para-kayak sitting in a slightly forward flexed trunk position and rotating the trunk and pelvis leads to an increase in paddling power output (Bjerkefors, Rosén, Tarassova, & Arndt, 2019).

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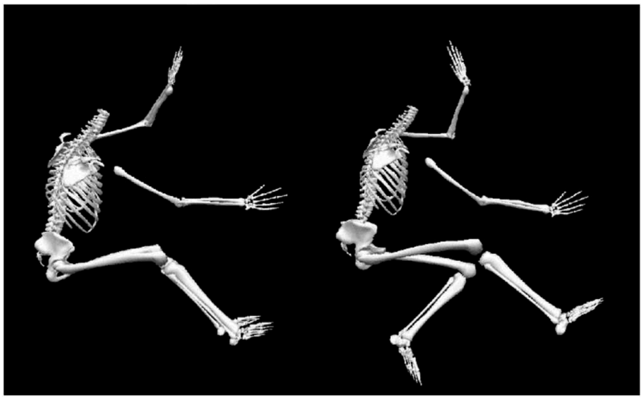

Figure 1. Illustration of two different seating positions common during Va'a paddling.

The leg on the paddling side of a crew boat paddler has previously been described (Sealey, 2010) to be positioned with the hip and knee flexed and pushing isometrically against the Va'a hull, whilst the non-paddling side foot is positioned beneath the seat (Figure 1). In V1 it is, however, common to sit with both legs in front (Figure 1) (West, 2014). No known study has however described how the legs contribute to the momentum of the Va'a.

While some kinematic and kinetic variables of competitive Va'a paddling have previously been reported (Haley & Nichols, 2009; Humphries et al., 2000; Kerr, Spinks, Leicht, Sinclair, & Woodside, 2008; Sealey et al., 2011; Sealey, Spinks, Leicht, & Sinclair, 2010), these are only described within the able-bodied population. More information specific for Para Va'a is therefore critical for the development of a new evidence-based classification system. Examining the ROM of the arms, trunk and legs during paddling and how impairments affect these movements and the paddling force, will assist in developing a theoretical model of the determinants of sport performance for Para Va'a. A comparative study is therefore required to examine if these variables differ between able-bodied and Para Va'a athletes during Va'a paddling. The purpose of this study was two-fold; first to examine joint angles, stroke frequency and paddling force in able-bodied and Para Va'a athletes during high intensity Va'a ergometer paddling and to determine whether differences exist based on functional capacity (e.g., athletes without impairment vs. athletes with trunk and bilateral leg impairment (TL), bilateral leg impairment (BL) and unilateral leg impairment (UL)). Secondly, to determine the relationship between joint angles and paddling force of able-bodied and Para Va'a athletes.

Method

Participants

Fifty-four Va'a athletes divided into two main and three subgroups volunteered to participate in this study. The first group consisted of 10 able-bodied Va'a athletes who competed at an international level (mean ± standard deviation (SD), 5 males: 46 ± 6 years, 80 ± 4 kg, 1.83 ± 0.08 m and 5 females: 44 ± 3 years, 72 ± 11 kg, 1.72 ± 0.05 m). The second group was comprised of 44 Para Va'a athletes; 37 competing at international and seven at national level (31 males: 35 ± 8 years, 77 ± 16 kg, 1.77 ± 0.17 m and 13 females: 33 ± 7 years, 58 ± 10 kg, 1.62 ± 0.13 m), from 15 different countries across six continents. The inclusion criteria for all participants were that they competed at a national or international level and followed an established training program. The para-athletes also had to have an impairment that deemed them eligible for competing in Para Va'a. Following verbal and written information participants provided written consent and completed a health declaration form. Ethical approval for the study was granted by the Regional Ethical Committee, Stockholm, Sweden.

The para-athletes were further divided into three subgroups; TL (n = 17), BL: (n = 10), and UL (n = 17), based on their results from the trunk and leg test in the international medical classification performed within the same year as the athlete's participation in the data collection. The trunk test consisted of six dynamic tasks where the athletes performed trunk flexion, extension, side bending and rotation to both sides while seated on a treatment bench. The leg test consisted of bilaterally testing active ankle, knee and hip flexion and extension and performing a leg press on each leg. All tasks were scored on a 0–2 scale with a total score of 12 for the trunk test and 28 points for the leg test. All athletes who scored 9 or lower in the trunk test and had a loss of points on both legs in the leg test were allocated to the TL group for this study. If the athletes did not have an impairment affecting the trunk and only lost points on one leg the athlete was allocated to the UL group whereas if the athlete lost points in both legs the athlete was allocated to the BL group.

Equipment

The Va'a paddling was performed on either a D1-M KayakPro Va'a ergometer (KayakPro, Miami, FL, USA) (n = 36 para-athletes) or a Concept 2 ergometer (Concept 2, Nottingham, England, UK) (n = 10 able-bodied athletes; n = 8 para-athletes) with an adaptation for Va'a paddling (Paddlesport Training Systems, East Hardwick, VT, USA). The ergometer settings were based on athletes' preference and fitting of adaptive equipment. Adaptive equipment was fitted so that it replicated the athletes' normal competition and training set-up as close as possible to increase ecological validity. Athletes used their own adaptive equipment where applicable, chose their preferred seating position and used their own preferred technique.

The resistance on both ergometers could be adjusted by regulating the air intake on the flywheel. The athletes chose their own preferred resistance. All able-bodied athletes chose a resistance of 10 (heaviest). The mean resistance for the female para-athletes was 3 ± 1 with a range of 0–4 and the mean resistance for the male para-athletes was 5 ± 2 with a range of 0–10.

Three-dimensional kinematic data were recorded using a 12-camera optoelectronic system (Oqus4, Qualisys AB, Gothenburg, Sweden) at a sampling frequency of 150 Hz. The system was calibrated according to the manufacturer's guidelines. The criteria for accepted calibration was that the camera residuals should not exceed 2 mm and that the SD for the length of the 602.3 mm wand should not exceed 1 mm. Between 39 and 68 reflective markers (12 mm diameter) were attached to anatomical

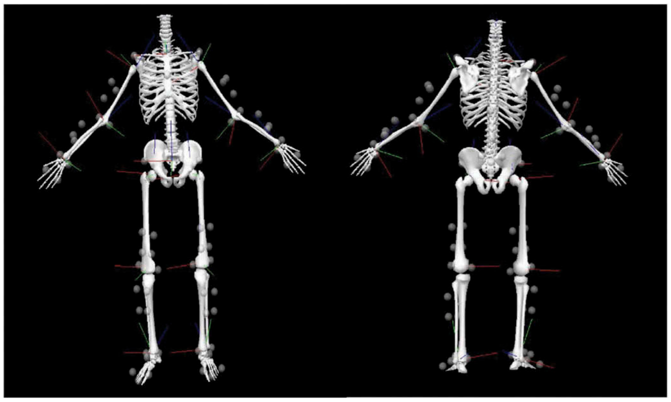

Figure 2. Whole body model consisting of 14 segments. The markers were attached at the following positions for the. (a) *hand and arm segments*: markers were attached bilaterally on the radial and ulnar styloid processes, the medial head of the second and the lateral head of the fifth metacarpals and on the lateral and medial humeral epicondyles. Clusters of three markers were placed on the upper arms and forearms, (b) *trunk segment*: markers were placed over the spine at C7, T5 and T12 level, on the center of the sternum and on the left and right acromion, (c) *pelvis segment*: markers were attached on the left and right anterior superior iliac spine (ASIS) and on the left and right posterior superior iliac spine (PSIS). One additional marker was placed on the sacrum level of the spine if any of the other markers were not visible. If an athlete used a seat with a high backrest and the PSIS markers were not visible, markers were placed on the seat at the corresponding level of the PSIS landmarks, (d) *leg and foot segments*: Clusters of four markers were attached bilaterally on the thigh, two markers were placed bilaterally on the lateral and medial part of the knee joint, clusters of four markers were placed bilaterally on the lower leg and markers were placed on the lateral and medial malleoli and the head of the first and fifth metatarsals. An additional three or four markers were placed on the foot as tracking markers. If the athletes were using a prosthesis, markers were positioned laterally and medially on the flexion axis of the prosthesis to simulate a knee and/or an ankle joint. A cluster of four markers was placed on the prosthesis. If the athletes were not using a prosthesis two markers were placed at the distal end of the residual limb and a cluster of four markers was placed on the residual limb, (e) *paddle*: one marker was attached on the paddle shaft and a reflective tape was attached on the middle of the force transducer.

landmarks in order to construct a whole-body model consisting of 14 segments (Figure 2) and one marker was placed on the Va'a paddle shaft. The number of markers depended on whether the athletes with limb deficiencies used their prosthesis or not. The marker placement was the same as in the study by Bjerkefors et al. (2019) (Figure 2).

A piezoelectric force transducer (Type 9311B, Kistler Instruments AG, Winterthur, Switzerland) was connected between the rope and the end of the paddle shaft to continuously measure force at a sampling frequency of 1500 Hz. The transducer was connected to an amplifier (Type 5073, Kistler Instruments AG, Winterthur, Switzerland) and signals were A/D converted (Qualisys AB, Gothenburg, Sweden).

Data collection procedure

Data collection was conducted during five different occasions and locations between 2014 and 2016. Three occasions were during the ICF World Championships in Sprint and Paracanoe. Prior to data collection, the athletes were introduced to the test procedure and if the para-athletes used adaptive seats or straps, these were attached on the Va'a ergometer. All athletes had previous experience with paddling on a Va'a ergometer. Athletes then performed a 10-min warm-up at a self-selected intensity. Thereafter, athletes were asked to choose their preferred paddling side (Figure 3) and paddle on that side at a high-intensity level, which was defined as the highest intensity that the athlete could stably maintain during 20 stroke cycles. The athletes were asked to maintain this intensity level through visual feedback of the power output on the ergometer display. After the athletes had paddled at this level, the athletes were asked if they could paddle at an even higher intensity. If so, the athletes rested for 5 min and then paddled at the higher level. None of the athletes paddled more than these two levels. The highest level the athletes could hold for 20 stroke cycles was used for analysis. Kinematic and kinetic data were simultaneously collected and synchronized using Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden).

Data processing

Kinematic and kinetic data analysis was performed in Visual3D (version 5, C-Motion, Inc., Germantown, MD, USA) and MATLAB (version R2016a, The MathWorks, Inc., Natick, MA, USA). Kinematic data were smoothed with a second-order, bi-directional, low-pass Butterworth filter with a 7 Hz cut-off frequency. The global coordinate system (GCS) was set with a positive X-axis in the direction the athlete was facing, a positive Y-axis directed to the left of the athlete and a positive Z-axis pointing upward. The segment coordinate system (SCS) for the pelvis segment originated from a mid-point between the markers placed on the anterior superior iliac spine (ASIS). The x-axis pointed towards the right ASIS, the z-axis was perpendicular to the x-y plane (defined as the plane passing through the right and left ASIS markers, and the mid-point of the right and left posterior superior iliac spine markers) and the y-axis was the cross product of the z and x-axes. The SCS for the other segments were defined using the proximal and distal endpoints of each segment in accordance with Visual 3D recommendations (Table 1). The SCS z-axis (inferior to superior) was determined by the unit vector

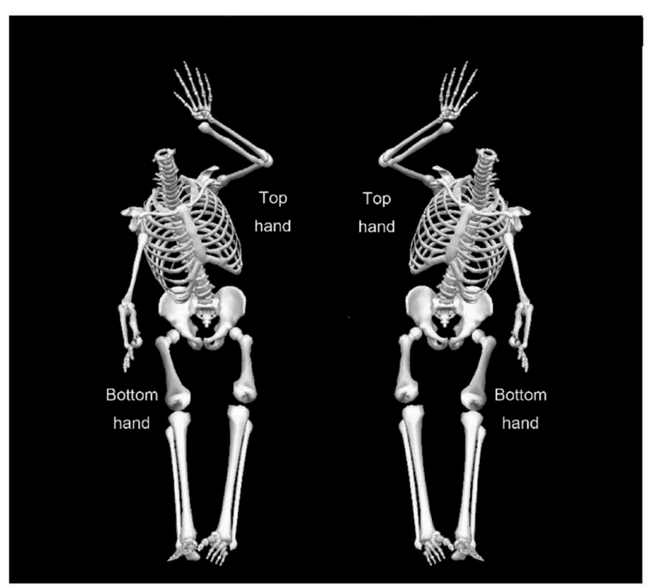

Figure 3. Illustration of top and bottom hand side for: (a) right bottom hand and (b) left bottom hand paddlers. Preferred paddling side is associated with the bottom hand on the paddle and the limbs on that side.

Table 1. Segment end point definitions.

Segment	Proximal end point	Distal end point
Upper arm	Shoulder joint landmark[a] defined as: Starting point: Acromion marker Existing segment: Thorax/Ab Axial offset: -(0.17*Acromion Distance)	Joint centre point defined as midway between the medial and lateral markers placed at the elbow
Forearm	Joint centre point defined as midway between medial and lateral markers placed at the elbow	Joint centre point defined as midway between medial and lateral markers placed at the wrist
Hand	Joint centre point defined as midway between medial and lateral markers placed at the wrist	Joint centre point defined as midway between medial and lateral markers placed at the hand
Trunk	Joint centre point defined as midway between right and left markers placed on the acromion	Joint centre point defined as midway between right and left markers placed on the ASIS
Thigh	Hip joint landmark[b] location defined as: Existing segment: Pelvis Medial/lateral offset: 0.36*ASIS Distance Anterior/posterior offset: −0.19*ASIS Distance Axial offset: −0.3*ASIS Distance	Joint centre point defined as midway between medial and lateral markers placed at the knee
Shank	Joint centre point defined as midway between medial and lateral markers placed at the knee	Joint centre point defined as midway between medial and lateral markers placed at the ankle
Foot	Joint centre point defined as midway between medial and lateral markers placed at the ankle	Joint centre point defined as midway between medial and lateral markers placed at the foot

[a]Shoulder joint landmark created as explained by Rab, Petuskey, and Bagley (2002)
bThe location of the hip joint centre landmarks are created automatically using Bell, Brand, and Pedersen (1989) and Bell, Pedersen, and Brand (1990) regression equations when creating a CODA pelvis in Visual 3D https://c-motion.com/v3dwiki/index.php/Hip_Joint_Landmarks.19891990https://www.c motion.com/v3dwiki/index.php/Hip_Joint_Landmarks

directed from the distal segment endpoint to the proximal segment endpoint. The SCS y-axis (posterior to anterior) was determined by the unit vector that was perpendicular to the frontal plane and z-axis. The SCS x-axis (medial to lateral) was determined by the right-hand rule. Maximal and minimal peak angles (max and min) and total ROM for flexion and extension were calculated for the shoulder, elbow, wrist, trunk, hip, knee and ankle joints (defined in Table 2). The angles were calculated using a Cardan/Euler rotation sequence of x, y, z which corresponded to forward flexion, abduction and axial rotation.

Additionally, max, min and ROM were calculated for shoulder rotation and abduction, trunk rotation, trunk and pelvis rotation and trunk bending. Since the Va'a paddling movement is asymmetric, the joint angle data were divided into "top hand side" and "bottom hand side" for the arms and legs (Figure 3). Kinematic data were also used to define the stroke cycle and to calculate stroke frequency using the marker on the paddle. One stroke cycle was defined from catch to catch. The catch was defined as the maximum position of the paddle in the positive X direction in the GCS (Bjerkefors, Tarassova, Rosén, Zakaria, & Arndt, 2018; Michael, Rooney, & Smith, 2012). The mean paddling force during each pull phase (defined from catch to the end of the pull phase i.e., the maximum position of the paddle in the negative X direction) was calculated. The mean paddling force of the first 10 pull phases and the max, min and ROM of the joint angles during the first 10 stroke cycles were used for the data analysis.

Statistical analysis

The statistical analysis was carried out in IBM SPSS statistics 24 (IBM, Armonk, NY, USA). All parameters are presented as means ± 1 SD. The Shapiro Wilks' W test was performed to test the data for normality. Levene's test for equality was conducted to examine if the group variances were equal in the population. For the variables which met the assumption of equality ($p < 0.05$), a one-way ANOVA with one between-group factor *group* (able-bodied, TL, BL, UL) was performed for comparisons of max, min and ROM for the shoulder, elbow, wrist, trunk, hip, knee and ankle, stroke frequency and mean paddling force. For the variables which did not meet the assumption of equality, the results from a Welch test were used instead of the ANOVA. Mean paddling force was divided into gender and group since gender has an impact on the force. Differences in mean paddling force between the groups were only examined for the males as the group sizes were too small for meaningful statistical analysis for the female groups (able-bodied = 5, TL = 6, BL = 3, UL = 4). Significant interaction effects were analysed using the Tukey-Kramer post-hoc test for variables with equal variances and Games-Howell for variables with unequal variances. Ninety-five percent confidence intervals (CI) and effect size for mean differences are reported. Eta-squared (η^2) was calculated as an estimate of effect size.

Correlation calculations were conducted to examine the relationship of max, min and ROM of the joints in arms,

Table 2. Joint angle definitions.

Moving segment	Reference segment	Designated joint movement
Upper arm	Trunk	Shoulder: flexion/extension, abduction/adduction and external/internal rotation
Forearm	Upper arm	Elbow: flexion/extension
Hand	Forearm	Wrist: flexion and extension
Trunk	Global Coordinate System (GCS)	Trunk: flexion/extension
Trunk	Global Coordinate System (GCS)	Trunk and pelvis: rotation*
Trunk	Pelvis	Trunk: bending, rotation
Thigh	Pelvis	Hip: flexion/extension
Shank	Thigh	Knee: flexion/extension
Foot	Shank	Foot: dorsal flexion/plantar flexion

*When the trunk rotation angle is defined in reference to the GCS the calculated angle includes the movement of the pelvis.

trunk and legs with mean paddling force. Spearman's correlation coefficient was calculated for mean paddling force, and all joint angles for the female able-bodied and Para Va'a athletes since mean paddling force was not normally distributed. For the male able-bodied and Para Va'a athletes, Pearson's correlation coefficient was calculated for mean paddling force and the arm and trunk joint angles and the Spearman's correlation coefficient was calculated for mean paddling force and leg joint angles. The level of significance was set at $p \leq 0.05$.

Results

The mean ± 1 SD stroke frequency was 81 ± 15, 59 ± 14, 67 ± 13 and 72 ± 15 strokes·min^{-1} for able-bodied, TL, BL, and UL, respectively. A significant group effect was seen ($F(3,50)$ = 5.78, p= 0.002, η^2 = 0.258) and the post-hoc test showed that able-bodied and UL had a significantly higher stroke frequency with a mean difference of 23 (95% CI, 8 to 38) strokes·min^{-1} and 14 (95% CI, 1 to 27) strokes·min^{-1} respectively, compared to TL.

The mean paddling force was 133 ± 21, 72 ± 14, 72 ± 10 and 78 ± 2 N for the able-bodied, TL, BL and UL female groups, respectively. For male athletes, the paddling force was 159 ± 19, 83 ± 17, 109 ± 20 and 113 ± 19 N for able-bodied, TL, BL and UL, respectively. A significant group effect for the male athletes was seen ($F(3,32)$ = 19.01, p< 0.001, η^2 = 0.641). The post-hoc test showed that male able-bodied had a significantly greater paddling force (p< 0.001) compared to male TL, BL and UL with a mean difference of 76 (95% CI, 49 to 104) N, 51 (95% CI, 21 to 81) N and 47 (95% CI, 20 to 73) N, respectively. Furthermore, male UL and BL had a significantly greater paddling force with a mean difference of 29 (95% CI, 9 to 50, p= 0.003) N and 25 (95% CI, 1 to 50, p= 0.042) N compared to male TL.

For the top hand side, able-bodied demonstrated significantly larger joint angle values compared to TL at shoulder flexion max and min, shoulder abduction min, shoulder internal rotation min and hip flexion ROM (Table 3). They also demonstrated larger joint angle values compared to BL in shoulder abduction min and hip flexion ROM and compared to TL, BL, and UL in the knee and ankle flexion ROM. UL exhibited larger values compared to TL in shoulder flexion min and hip flexion ROM, and compared to BL in shoulder abduction min.

On the bottom hand side able-bodied had significantly larger values compared to TL in shoulder flexion max and min and shoulder internal rotation min, compared to UL in shoulder flexion max, and compared to BL and TL in hip, knee and ankle flexion ROM. UL exhibited larger values compared to TL in hip and knee flexion ROM, and compared to BL in knee and ankle flexion ROM (Table 4).

For the trunk, able-bodied showed larger values compared to TL in trunk flexion max and min, trunk and pelvis rotation at catch and release, and ROM, as well as in trunk rotation ROM. Able-bodied also exhibited larger values in trunk flexion min compared to BL, and in trunk bending ROM compared to UL. Furthermore, BL and UL had larger

Table 3. Peak joint angles and ranges of movement (ROM) in degrees during high intensity Va'a ergometer paddling of the arms and legs for the top hand side on the paddle for able-bodied athletes (AB) and para-athletes when divided into different impairment groups: athletes with trunk and bilateral leg impairment (TL), athletes with bilateral leg impairment (BL) and athletes with unilateral leg impairment (UL).

		Top hand side					
		AB	TL	BL	UL		
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Sign. diff	ES
Shoulder	Flexion (max)	122 ± 19	102 ± 18	119 ± 14	117 ± 17	a	0.182
	Flexion (min)	64 ± 14	24 ± 26	46 ± 19	49 ± 20	a, e	0.333
	ROM	58 ± 17	78 ± 26	73 ± 22	68 ± 26		0.086
	Abduction (max)	36 ± 16	42 ± 15	33 ± 17	32 ± 20		0.061
	Abduction (min)	4 ± 5	−4 ± 6	−8 ± 7	1 ± 8	a, b, f	0.300
	ROM	32 ± 15	46 ± 17	40 ± 19	30 ± 16	e	0.150
	Internal rotation (max)	67 ± 32	49 ± 14	57 ± 13	51 ± 14		0.119
	Internal rotation (min)	34 ± 25	7 ± 26	26 ± 22	21 ± 19	a	0.157
	ROM	33 ± 15	42 ± 24	31 ± 12	30 ± 19		0.066
Elbow	Flexion (max)	78 ± 14	94 ± 24	79 ± 12	78 ± 17	e	0.163
	Flexion (min)	48 ± 13	43 ± 7	41 ± 10	42 ± 14		0.042
	ROM	30 ± 10	52 ± 25	37 ± 14	36 ± 15	a^{GH}	0.189
Wrist	Flexion	19 ± 8	29 ± 17	20 ± 12	24 ± 15		0.068
	Extension	10 ± 19	−4 ± 14	0 ± 10	−4 ± 15		0.124
	ROM	29 ± 20	25 ± 15	20 ± 4	20 ± 7		0.080
Hip	Flexion (max)	80 ± 17	78 ± 12	91 ± 14	83 ± 27		0.059
	Flexion (min)	63 ± 17	73 ± 11	83 ± 14	70 ± 24		0.116
	ROM	17 ± 8	5 ± 4	8 ± 4	13 ± 8	a, b, e^{GH}	0.364
Knee	Flexion (max)	55 ± 7	48 ± 26	33 ± 33	40 ± 31		0.076
	Flexion (min)	43 ± 8	45 ± 25	30 ± 31	33 ± 31		0.060
	ROM	12 ± 3	3 ± 2	3 ± 3	7 ± 6	a, b, c^{GH}	0.371
Ankle	Flexion (dorsi)	−19 ± 9	−19 ± 12	−13 ± 15	−18 ± 16		0.025
	Flexion (plantar)	27 ± 9	21 ± 13	15 ± 17	21 ± 18		0.062
	ROM	8 ± 3	2 ± 2	2 ± 2	3 ± 3	a, b, c^{GH}	0.468

The values presented are the group means ± 1 standard deviation (SD), the significant differences (p ≤ 0.05) between groups (Sign. Diff) and the effect size (ES) of the joint angle. ^{GH} Interactions were analysed using Games-Howell posthoc test. All other interactions were analysed using Tukey-Kramer.
a = Significant difference between able-bodied athletes and TL
b = Significant difference between able-bodied athletes and BL
c = Significant difference between able-bodied athletes and UL
d = Significant difference between TL and BL
e = Significant difference between TL and UL
f = Significant difference between BL and UL

Table 4. Peak joint angles and ranges of movement (ROM) in degrees during high intensity Va'a ergometer paddling of the arms and legs for the bottom hand side on the paddle for able-bodied athletes (AB) and para-athletes when divided into different impairment groups: athletes with trunk and bilateral leg impairment (TL), athletes with bilateral leg impairment (BL) and athletes with unilateral leg impairment (UL).

Bottom hand side							
		AB	TL	BL	UL		
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Sign. diff	ES
Shoulder	Flexion (max)	88 ± 18	61 ± 16	79 ± 14	70 ± 18	a, c, d	0.274
	Flexion (min)	−12 ± 20	−45 ± 27	−32 ± 12	−27 ± 14	a^{GH}	0.267
	ROM	100 ± 19	106 ± 26	111 ± 21	97 ± 19		0.060
	Abduction (max)	46 ± 8	49 ± 16	40 ± 13	43 ± 10		0.078
	Abduction (min)	17 ± 7	19 ± 6	17 ± 8	15 ± 6		0.067
	ROM	29 ± 11	30 ± 15	22 ± 10	28 ± 11		0.056
	Internal rotation (max)	61 ± 19	48 ± 10	44 ± 14	45 ± 16	c	0.155
	Internal rotation (min)	8 ± 20	−17 ± 22	−8 ± 20	−6 ± 17	a	0.175
	ROM	53 ± 16	65 ± 25	53 ± 18	51 ± 19		0.088
Elbow	Flexion (max)	87 ± 12	76 ± 22	80 ± 17	78 ± 26		0.036
	Flexion (min)	29 ± 14	34 ± 9	33 ± 6	36 ± 9		0.061
	ROM	58 ± 20	42 ± 22	48 ± 19	42 ± 23		0.078
Wrist	Flexion	21 ± 13	17 ± 13	10 ± 10	19 ± 8		0.103
	Extension	7 ± 23	7 ± 28	7 ± 16	1 ± 19		0.016
	ROM	28 ± 21	24 ± 19	17 ± 9	20 ± 14		0.054
Hip	Flexion (max)	81 ± 17	80 ± 14	83 ± 32	89 ± 28		0.026
	Flexion (min)	61 ± 15	74 ± 12	75 ± 29	74 ± 24		0.063
	ROM	20 ± 11	6 ± 5	9 ± 6	15 ± 8	a, b, e^{GH}	0.375
Knee	Flexion (max)	51 ± 9	54 ± 24	37 ± 27	43 ± 15		0.110
	Flexion (min)	31 ± 9	50 ± 24	31 ± 26	26 ± 13	e	0.223
	ROM	20 ± 8	4 ± 3	6 ± 4	16 ± 11	a, b, e, f^{GH}	0.442
Ankle	Flexion (dorsi)	−23 ± 10	−20 ± 14	−14 ± 17	−19 ± 9		0.046
	Flexion (plantar)	35 ± 11	23 ± 15	17 ± 18	27 ± 12		0.135
	ROM	12 ± 4	3 ± 2	3 ± 2	8 ± 6	a, b, f^{GH}	0.385

The values presented are the group means ± 1 standard deviation (SD), the significant differences ($p \leq 0.05$) between groups (sign. Diff) and the effect size (ES) of the joint angle. ^{GH} Interactions were analysed using Games-Howell posthoc test. All other interactions were analysed using Tukey-Kramer.
a = Significant difference between able-bodied athletes and TL
b = Significant difference between able-bodied athletes and BL
c = Significant difference between able-bodied athletes and UL
d = Significant difference between TL and BL
e = Significant difference between TL and UL
f = Significant difference between BL and UL

Table 5. Peak joint angles and ranges of movement (ROM) in degrees during high intensity Va'a ergometer paddling of the trunk for able-bodied athletes (AB) and para-athletes when divided into different impairment groups: athletes with trunk and bilateral leg impairment (TL), athletes with bilateral leg impairment (BL) and athletes with unilateral leg impairment (UL).

		AB	TL	BL	UL		
		Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Sign. diff	ES
Trunk	Flexion (maximum)	31 ± 14	−2 ± 15	16 ± 10	19 ± 13	a, d, e	0.469
	Flexion (minimum)	15 ± 10	−11 ± 11	2 ± 8	5 ± 6	a, b, d, e^{GH}	0.524
	ROM	16 ± 9	9 ± 5	14 ± 7	14 ± 9		0.129
	and pelvis rotation (catch)	27 ± 9	15 ± 11	19 ± 8	19 ± 11	a	0.150
	and pelvis rotation (release)	20 ± 9	9 ± 8	13 ± 6	20 ± 8	a, e	0.295
	ROM	47 ± 11	24 ± 13	33 ± 8	40 ± 14	a, e	0.340
	Rotation (catch)	18 ± 12	10 ± 9	14 ± 8	14 ± 7		0.091
	Rotation (release)	15 ± 6	11 ± 6	14 ± 6	14 ± 4		0.076
	ROM	33 ± 13	21 ± 11	28 ± 7	28 ± 9	a	0.156
	Bending (catch)	11 ± 12	4 ± 11	7 ± 10	5 ± 10		0.064
	Bending (release)	−7 ± 10	−9 ± 12	−7 ± 8	−4 ± 9		0.047
	ROM	18 ± 9	13 ± 6	14 ± 6	9 ± 3	c, e^{GH}	0.264

The values presented are the group means ± 1 standard deviation (SD), the significant differences ($p \leq 0.05$) between groups (sign. Diff), the effect size (ES) of the joint angle. ^{GH} Interactions were analysed using Games-Howell posthoc test. All other interactions were analysed using Tukey-Kramer.
a = Significant difference between able-bodied athletes and TL
b = Significant difference between able-bodied athletes and BL
c = Significant difference between able-bodied athletes and UL
d = Significant difference between TL and BL
e = Significant difference between TL and UL
f = Significant difference between BL and UL

values in trunk flexion max and min compared to TL, whilst UL also had larger values in trunk and pelvis rotation release and ROM (Table 5).

Significant positive correlations were found for both males and females between mean paddling force and top hand side hip flexion ROM, as well as bottom hand side shoulder flexion max and hip, knee and ankle flexion ROM. Trunk variables that significantly correlated with mean paddling force were trunk flexion max, min and ROM, trunk and pelvis rotation at catch and ROM, as well as trunk rotation at catch and ROM (Table 6).

Table 6. Significant correlations for male and female able-bodied and Para Va'a athletes between mean paddling force and joint angles of the arms and legs for the top and bottom hand side on the paddle and the trunk during high intensity Va'a ergometer paddling. Values are only presented when significant correlations were seen for both genders.

		Males		Females	
		r-value	*p*-value	r-value	*p*-value
Top hand side	Hip flexion ROM	0.568	<0.001	0.585	0.014
Bottom hand side	Shoulder flexion max	0.462[a]	0.005	0.842	<0.001
	Hip flexion ROM	0.624	<0.001	0.652	0.005
	Knee flexion ROM	0.542	0.001	0.504	0.039
	Ankle flexion ROM	0.370	0.026	0.735	0.001
Trunk	Flexion max	0.677[a]	<0.001	0.798	<0.001
	Flexion min	0.606[a]	<0.001	0.811	<0.001
	Flexion ROM	0.449[a]	0.007	0.638	0.006
	and pelvis rotation Catch	0.417[a]	0.013	0.508	0.037
	and pelvis rotation ROM	0.687[a]	<0.001	0.562	0.019
	Rotation Catch	0.395[a]	0.019	0.569	0.017
	Rotation ROM	0.546[a]	0.001	0.637	0.006

[a]Pearson correlation coefficient. All other correlations are Spearman's rank correlation coefficients.

Discussion

The purpose of this study was to examine joint angles, stroke frequency and paddling force in able-bodied and Para Va'a athletes during high-intensity Va'a ergometer paddling to determine if differences existed based on functional capacity and to examine the relationship between joint angles and paddling force. In general, less impaired para-athletes and able-bodied athletes demonstrated larger paddling forces and joint ROM in trunk flexion max and min and bottom hand side hip, knee and ankle flexion. Furthermore, the able-bodied athletes exhibited larger joint ROM in top hand side knee and ankle flexion compared to the para-athletes. Trunk flexion max, min and ROM, trunk rotation and trunk and pelvis rotation at catch and ROM, and top hand side hip flexion ROM and bottom hand side hip, knee and ankle flexion ROM were significantly positively correlated with mean paddling force for both males and females.

Dascombe, Stanton, Peddle, Evans, and Coutts (2002) found that a stroke rate of 80–90 strokes·min^{-1} provided the greatest force production in outrigger canoe paddlers which corresponds to the mean stroke frequency found in the able-bodied athletes in this study (81 ± 15 strokes·min^{-1}). The able-bodied group's stroke frequency in this study was significantly higher only compared to the TL group, whereas their mean paddling force was significantly higher compared to all para-athlete groups which demonstrates that the higher stroke frequency alone did not result in higher mean paddling force.

Since athletes with impairments only affecting the arms are not eligible to compete in Para Va'a at international events organised by the ICF, no differences were anticipated between the able-bodied group and the Para Va'a groups in arm joint ROM. The results, however, showed that the able-bodied group had a larger shoulder flexion max and min value for both the top and bottom hand side compared to the TL group. Since the shoulder flexion angle is calculated as the angle between the upper arm and the trunk, leaning forward with the trunk with a concomitant constant upper arm angle will increase shoulder flexion max. The TL group cannot lean forward with their trunk due to their impairment which may explain why the able-bodied group demonstrated larger shoulder flexion values and why there was a positive correlation between mean paddling force and bottom hand side shoulder flexion for both males and females. In a study by Bjerkefors et al. (2019) para-kayak athletes with the most severe impairment exhibited larger shoulder extension values compared to able-bodied kayak athletes. This was also found in the present study where the TL group exhibited greater shoulder extension for the bottom hand side compared to the able-bodied group. Bjerkefors et al. (2019) suggested that the increased shoulder extension in athletes with no or limited trunk and leg function was due to the athletes compensating for their impairment by depending upon their arm function for power production, which is presumably also the case for the TL athletes in this study.

Trunk movement during Va'a paddling can differ depending on what technique the athlete uses (Sealey et al., 2011). As previously mentioned, the Va'a paddling technique includes a combination of trunk flexion/extension and trunk rotation but there can be a larger movement in either trunk flexion/extension or trunk rotation depending on if the athlete uses the Hawaiian or the Tahitian style. In the present study, all the athletes exhibited both trunk rotation and trunk flexion. The trunk flexion ROM value was 16 ± 9° which is similar to a previous reported value of 17 ± 14° which was exhibited by able-bodied Va'a athletes using the Hawaiian technique (Sealey et al., 2011). The able-bodied, BL and UL groups demonstrated significantly larger trunk flexion max and min values compared to the TL group, meaning that they leaned more forward with their trunk. The athletes in the TL group sat with their trunk in extension (negative values for trunk flexion max and min) whereas the able-bodied, BL and UL groups never went into trunk extension. This is not surprising since the athletes in the TL group have an impairment affecting their trunk restricting the functional capacity to lean forward and therefore have to lean against the seat backrest. These results are similar to results found in para-kayak and cross-country sit-skiing where athletes with less impairment demonstrated larger trunk movement compared to athletes with more impairment (Bjerkefors et al., 2019; Rosso et al., 2016). Furthermore, the largest effect sizes and correlation values were seen in trunk flexion max and min demonstrating that the ability to sit in a forward leaning position with the trunk is of importance during Va'a paddling. Trunk rotation and trunk and pelvis rotation ROM were also positively correlated with mean paddling force for both male and female athletes indicating that being able to rotate the trunk and pelvis is also important. Trunk movement, therefore, seem to contribute to an increased paddling force, similarly to para-kayak and cross-country sit-skiing where larger trunk movement has been shown to contribute to increased paddling power output and the total force generated for propulsion, respectively (Bjerkefors et al., 2019; Rosso et al., 2016).

The ROM in the hip, knee and ankle of the bottom hand side leg in the able-bodied athletes in this study suggests that the leg does not only push in an isometric contraction as previously explained in outrigger crew paddlers (Sealey, 2010). The bottom hand side leg seemed to have a more important role in the production of force compared to the top hand side leg, as it was only the bottom hand side knee and ankle flexion ROM that was significantly correlated with mean paddling force. Interestingly, 14 out of the 17 athletes in the UL group had their non-impaired leg as the bottom hand side leg which indicates that this leg is more important when producing force. Having the non-impaired leg on the bottom hand side is presumably also the reason why no significant differences were found between the UL and able-bodied groups on the bottom hand side hip, knee and ankle flexion ROM. It was also in the bottom hand side leg differences between the para-athlete groups were observed where the UL group had significantly larger ROM in the knee and ankle compared to the BL group and in hip and knee compared to the TL group.

The results showed that the top hand side knee and ankle flexion ROM were not correlated with mean paddling force. Interestingly, the only notable difference in joint ROM between the able-bodied and UL athletes was in top hand knee and ankle flexion even though the able-bodied athletes demonstrated a significantly higher mean paddling force. It, therefore, seems that the top hand side leg does indeed have a role in paddling force production. Furthermore, the only differences between the BL and UL groups were in bottom hand side knee and ankle flexion ROM. Since no differences were found in the mean paddling force between these two groups which both have full trunk function, it may be that the movement of the legs is of less importance compared to the trunk. This is also indicated by the TL group exhibiting significantly less trunk flexion max and min values and mean paddling force compared to the BL and UL groups. The results, therefore, suggest that athletes who have full trunk function might be able to compete in the same classification class regardless of whether they have a bi- or unilateral leg impairment.

One of the limitations of this study is that it was performed on Va'a ergometers. It can only be speculated whether the joint ROM and mean paddling force would have been different on water. However, testing in a laboratory environment has the benefits that the conditions can be standardised and the weather and wind do not affect the outcome. A further limitation is that two different Va'a ergometers were used. These were required for the athletes to be able to use their ergometer specific adaptive equipment. Since the athletes were tested with their adaptive equipment, the athletes sat in individual positions which could also be a possible limitation. It would however not have been possible to restrict the usage of adaptive equipment since many of the athletes would not have been able to perform the test. Finally, it should be noted that if Va'a athletes have a technique which requires switching paddling side during a race, the top and bottom hand sides alternate. This study only examined paddling on the athlete's preferred side and, therefore, no conclusions can be drawn on the effect of alternating sides. Only V1 flat-water races over 200 m will be initially included in the Paralympic Games and in this event, many athletes predominately paddle on their preferred paddling side.

Conclusion

The study provides valuable information about differences in kinematic factors between able-bodied and Para Va'a athletes with different functional abilities affecting trunk and/or legs when paddling on a Va'a ergometer at a high-intensity level and the relationship between these variables with mean paddling force. The abilities to sit in a forward leaning position with the trunk, to rotate the trunk and pelvis and to move the leg of the bottom hand side of the paddle seem to be key kinematic factors during Va'a paddling. Athletes with full trunk function and either unilateral or bilateral leg impairment produced similar mean paddling force, which indicates that these athletes could possibly compete in the same class. The information from this study is relevant for creating an evidence-based sport-specific classification for Para Va'a.

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