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ORIGINAL PAPER

User-centered design of an innovative foot stretcher for ergometers to enhance the indoor rowing training

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Abstract

In this paper we present the design, prototyping and validation of a novel adjustable foot stretcher for indoor rowing training. The overall process is user-centered, in the sense that the athletes are directly involved in all the phases of the product development, from conceptual design to evaluation and validation. The conceptual design starts from well-known rowers needs. Accordingly, two design factors are selected to parametrize the prototype, namely the inter-axle spacing feet and the foot angle. The experimental evaluation and validation involve two phases, one based on a quantitative analysis of the performance, one based on subjective questionnaires submitted to the athletes. The performance-based analysis comprises the derivation of three pressure indices and one power transmission index. Indeed, the subjective analysis regards the users comfort and power transmission feelings. The results of both evaluations testify that an improvement in performance and comfort of the indoor rowing training session can be achieved.

Keywords User-centered design · Robust design · Sports engineering · Sports equipment and technology · Performance evaluation

1 Introduction

The rowing is a sport which is part of the program of Olympic games since 1900. It is defined by the rule number 1 of Rules of Racing and Related bye-laws 2017 of FISA (from the french, Fédération Internationale des Sociétés d'Aviron), as *the propulsion of a displacement boat, with or without coxswain, by the muscular force of one or more rowers, using oars as simple levers of the second order and sitting with their backs to the direction of movement of the boat* [1]. The sport gesture simulated on a machine, called rowing ergometer, is also considered as rowing [1]. The rowing ergometer consists of a braking mechanism (hydrodynamic, aerodynamic, magnetic, or combined with inertial) connected to a chain through a handlebar. The main component of its structure is a base where a series of components are mounted: the braking mechanism, the foot stretcher (where rowers places their feet) and the sliding seat (where rowers places their buttock) [2]. The foot stretcher is illustrated in Fig. 1 [3]. It is composed by two flex foot placed on two support platforms (with a fixed obliquity, inter-axle spacing feet and foot angle) covered by a toe block. The vertical position of the foot stretcher might shift up to the plate by varying its position on a scale (see, e.g. Fig. 2). Two-foot straps ensure the correct position of the athlete's feet.

Despite the biomechanics of the boat and the ergometer are different, this instrument is widely used for training and research studies [4]. In addition, as part of the training programs of rowers, indoor rowing represents a useful practice when weather conditions do not allow outdoor training [4]. In the practice of indoor training, the athlete and the machine constitute a closed kinematic chain. The repetition and the technique in performing a basic action called *rowing stroke*

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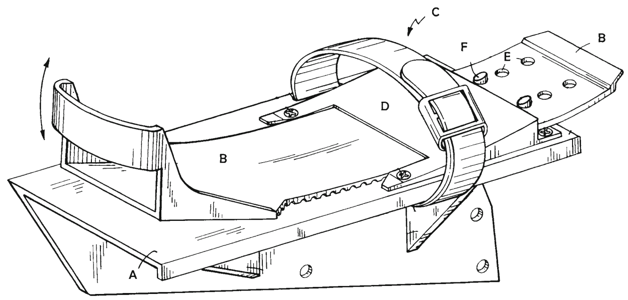


Fig. 1 Main components: **A** support platform; **B** flex foot; **C** foot strap; **D** toe block; **E** holes to regulate the vertical position of the foot stretcher using a pair **F** of posts extended perpendicularly to the support platform

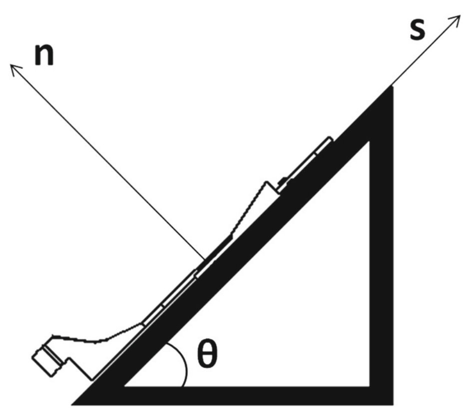


Fig. 2 Lateral view. Axis *s* is the direction where it is possible to regulate the height of the foot stretcher, while axis *n* is the direction perpendicular to the support platform

are decisive to ensure that the applied force is maximized. Rowing stroke is divided into two main phases: *drive* and *recovery* [5]. The first phase starts with the catch event, which occurs when the rowers lower limbs are at the maximum flexion and the upper limbs in maximum extension. From this event, the rowers extend the legs and flex the arms, reaches the applied maximum force until he reaches the last instant of drive phase, i.e. the finish event, when the lower limbs are in full extension while the upper limbs are in full flexion. After, there is a recovery phase during which the athlete, starting from the finish posture, returns in the catch position of the next stroke. For a graphical interpretation of the rowing phases, see Fig. 3.[1] During the overall gesture, the rower has only three direct contacts with the boat or ergometer itself, namely the sliding seat, the oars or the handlebar and the stationary foot stretcher. The latter element plays a crucial role in the rowing. Indeed, during the stroke, the rower generates most of the force and power by the legs, not by the back and arms [5]. Thus, the feet position is crucial for the leg propulsion efficiency. The foot stretcher's main objective is to provide a surface from which the rower can push. Within the rowing cycle, the foot stretcher is particularly important in the drive phase, during the execution of the squat movement. The foot stretcher's design differs for indoor and outdoor training. On the boat, the foot stretcher varies in complexity and adjustability, while on the ergometer, it has a limited adjustability. Usually, on the ergometer, the foot stretcher has only the adjustments for the height, while the inter-axle spacing feet and foot angle preferences are fixed. Currently, in outdoor training, the inter-axle changes as function of the boat typology (in a Single, the feet positions are closer compared to an Eight). Since the standard configuration of the ergometer is not suited for all athletes, this could affect the efficiency of their gesture. Hence, the standard fixed setting might reduce the comfort and the good power transmission of the athletic gesture. In addition, since it results difficult to reproduce the correct movements, the fixed setting of the foot stretcher might lead to possible injuries for the athletes. On this basis, to enhance the current practice of indoor rowing training, a study to investigate the performance of an adjustable foot stretcher for ergometers is required. Moreover, the process to design a novel adjustable foot stretcher has to involve the athletes, which represent the main end-users. Nowadays, many methodologies for product design and development start from the users' needs. This helps the design team to take into consideration the anthropometric characteristics and the subjective feelings of common users, in parallel with more objective performance indices. In order to involve subjective customer feelings into the design, a possible way is to use classical methods of participatory design, as *Kansei Engineering* [6,7] or *Kano* [8], which allow the identification of quality elements satisfying both functional and emotional user needs. In these techniques, the visual interaction between users and final product is possible through sketches or 3D CAD models. Usually, multiple alternatives are proposed for one product, each one with proper advantages and disadvantages. One of the most critical phases of the design is the concept selection of the best alternatives [9]. In this phase, multiple criteria decision-making methods, as the fuzzy analytic hierarchy process (AHP) [10,11] can be used. Recently, to enable this phase in practical situations, a distributed software platform has been developed, named ELIGERE [12,13]. Typical scenarios used for the evaluation of the alternatives can be both experiments and virtual reality tests. In the first case, a real prototype of the product is required, and participants have to be representative of the reference population. In the second case, CAD and digital human models [14,15] are used for simulating respectively the product and the reference population. Over the past years, many authors used different interactive design methodologies in various fields. In automotive, Lanzotti [16] used a robust design approach to identify the optimal level for the main design factors of the new car packaging where the

[1] http://www.concept2.com/files/pdf/us/training/.

score of the optimal solution is insensitive to anthropometric variability. The experimental validation was conducted in virtual environment by digital human model (Jack, Siemens). In manufacturing, Signore et al. [17], proposed a virtual reality approach to design and control a robotic cell for precision assembly. In healthcare, Grazioso et al. [18], proposed a hybrid design methodology to develop a novel instant 3D body scanner for the digital fabrication of prostheses and orthoses. The optimal solution design was selected by a multiple criteria decision-making session and the experimental validation was carried out on a real orthosis case. In sport, Di Gironimo et al. [19–21], to solve the current problem of illegal loss of ground contact phase in race-walking, proposed the use of the participatory design approach (through the Kansei Engineering approach) to develop an innovative system based on a wearable inertial system. The experimental laboratory and outdoor tests permitted to evaluate the preliminary performance of the optimal concept that is insensitive to anthropometric variability. In the context of indoor rowing, this paper aims at presenting a preliminary study to evaluate the design of a novel adjustable foot stretcher. To provide a foot stretcher which results adjustable and suitable to any athlete, independently by his anthropometric measurements, we design a mobile system to adapt the distance between the feet position. The novelty with respect to existing design solutions resides in the introduction of a parametric inter-axle spacing feet I and foot angle α. According to the specific characteristic of the rowing population, a real scenario for the evaluation phase is chosen. A physical prototype of the product is built and a group of athletes (representative of the Italian rowers population) is involved in its design. Finally, a specific experimental task protocol is developed to evaluate the system. The quantitative performance of the proposed design solution has been evaluated through the power transmission data and a specific index connected with the body pressure on the sliding seat. The qualitative evaluation is carried out by using a multiple criteria decision-making method through the ELIGERE framework. This method allows a user-centered evaluation of the design, since in this phase we involved directly the athletes that participated to the experimental phase. The improvements of the enhanced ergometer with respect to the classical one are validated also through a statistical analysis of the results.

2 Methodology

The conceptual design starts from the main rowers' needs related to the foot stretcher. As explained in the introduction, the standard configuration of the ergometer is not suited for all athletes (with problems related to efficiency of the gesture and possibility of injuries). On this base, the aim of the study is to define a design setting of the foot stretcher which could be more suitable to anthropometric variability. We choose the robust design methodology because it is an powerful tool to take into consideration the anthropometric noise factors in the process of the interactive design. Figure 4 shows the p-diagram of the robust design approach used as proposed in [22]. As described in the introduction, within the design parameter of the foot stretcher, the main *control factors* are: (i) height of flex foot s; (ii) interaxle spacing feet I; (iii) foot angle α; (iv) obliquity of support platform θ. Currently, only the first one is adjustable, while the others are fixed. In order to define new *adjustable Factors*, we develop a physical prototype of adjustable foot stretcher, which results suitable to anthropometric variability, from now named Novel Adjustable Inter-axle Foot stretcher (NAIF). It overcomes some limits of existing foot stretcher, by providing extra parametric regulations for the foot, the inter-axle spacing feet and the foot angle. In the biomechanics of the rowers, anthropometric variability can be considered the *noise factor*. For the foot stretcher, currently the only considered dimensions of human body is the foot length. The rowers can modify the height of flex foot in order to place the forefoot at the same level of the foot strap. In this study, we assume the pelvis width (strictly related to the distance between hip joint centers) as an addition noise factor. Indeed, according to the indications of rowing experts for a correct execution of gesture the interaxle spacing foot have to be equal at the distance between hip joint centers. So, the *user ergometer interaction* is evaluated through real experiments. The experimental validation phase is carried out with eight rowers with different anthropometric characteristics, competition level and hand side. Following the opinion of the rowing experts, we define the configurations useful for the NAIF validation (with only the value I adjustable). The *response* is composed by a quantitative and qualitative analysis. The first evaluation is carried out using power transmission data and body pressure one. The power transmission data recorded by ergometer offer a first estimation of the performance. The body pressure data are collected using a mat located on the sliding seat. They allow to evaluate useful indices (related to sink and disequilibrium) can be influence the real performance on the water. The qualitative evaluation is carried out through a distributed framework called ELIGERE. It allows an user center study based on multiple criteria decision making (MCDM).

3 Physical prototyping: design and development

The commercial ergometer used in this work is Model C from Concept2.[2] Figure 5 illustrates the developed prototype.

[2] http://www.concept2.it/service/indoor-rowers/model-c.

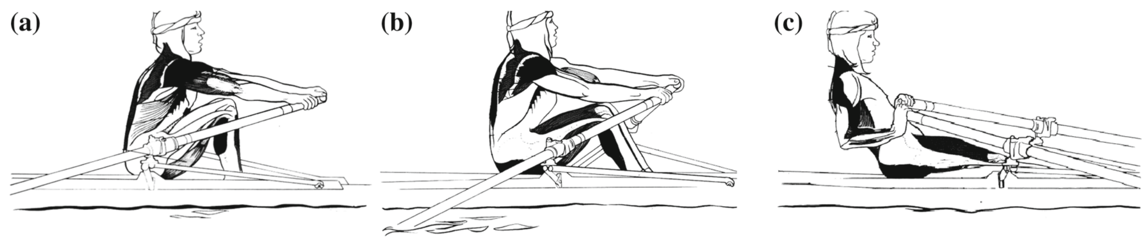


Fig. 3 Main rowing phases: **a** the first instant of drive phase (catch event); **b** the instant, during the drive phase, in which the athlete generates the maximum power from the legs; **c** the last event of drive phase (finish event)

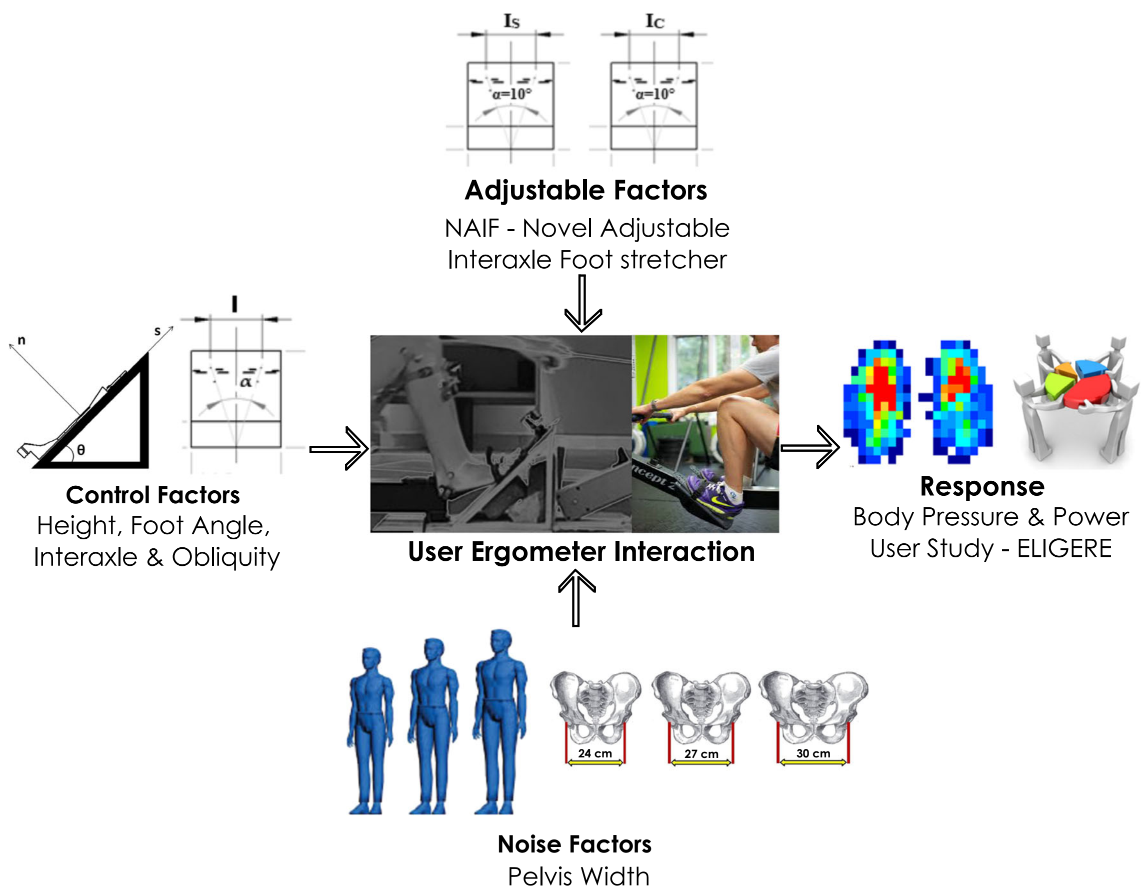


Fig. 4 P-diagram showing the robust design approach adopted for the innovative foot stretcher

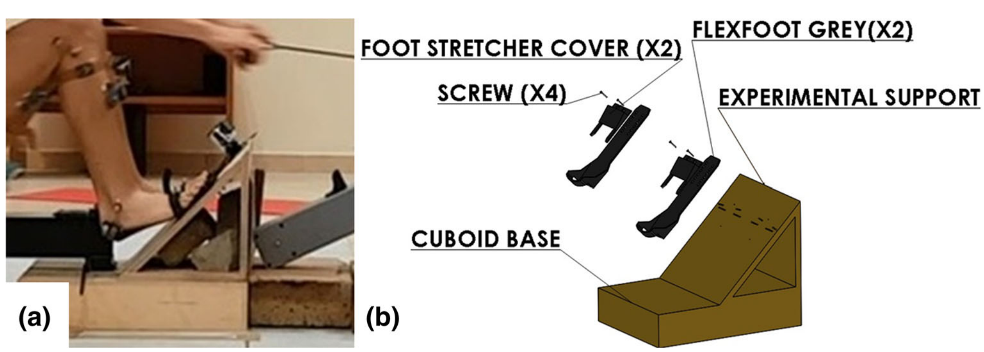


Fig. 5 Foot stretcher: **a** physical prototype; **b** virtual prototype

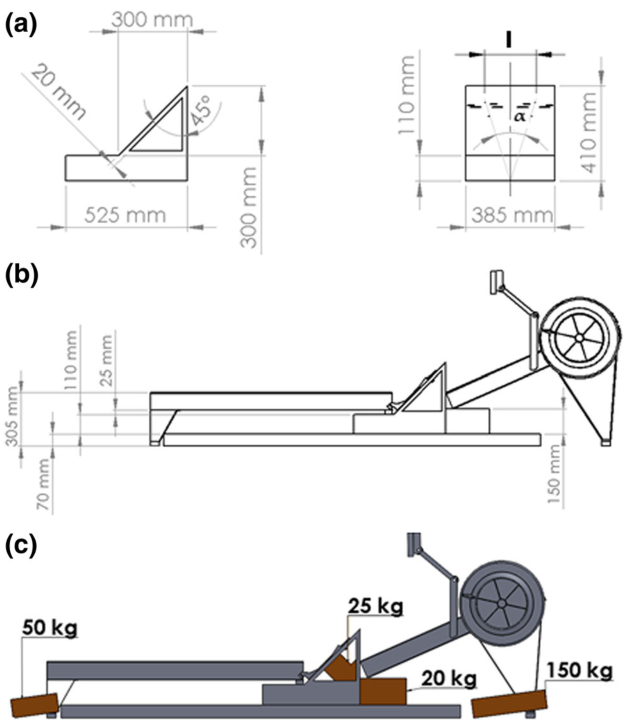


Fig. 6 Experimental setup: **a** technical drawing of the novel foot stretcher; **b** technical drawing of the full system (ergometer plus novel foot stretcher); **c** view with the stabilizing masses

In the standard configuration, the design parameters of the foot stretcher I and α are fixed respectively equal to 205 mm and equal to 10°. As we can see from the bottom of Fig. 6, we built a physical prototype (NAIF) that allows to position the feet with three configurations (0°; 10°; 20°). In addition, it gives an adjustable range for the design parameter I between 170 and 220 mm. We obtain these angles and adjustable range through inclined buttonhole couples which allow the Flexfoot Grey (therefore feet position) translation, by using an easy system of screws and nuts.

In order to define the control factor θ, the experimental support is composed by three planks of plywood assembled together by the nails, to provide a triangular cross section giving to the feet interface an obliquity of 45°. Below the experimental support a cuboid base guarantees the same standard height for the seat track. Furthermore, it avoids unwanted swings due to the elimination of the standard link constraint with the anterior part of the ergometer next to the fly-wheel, in order to incorporate the feet experimental support. Since the standard seat track is in horizontal condition and the experiments are carried out on Force Platform (BTS-P6000) which has a height of 70 mm, the cuboid base height is 110 mm to save the above condition (see top of Fig. 6). For the experimental setup, we eliminate the link constraint between the anterior and posterior part of the ergometer. In this way, the ergometer, which is an isostatic system, turns out to be labile. Above the inclined surface, the original parts (Flex foot Grey; Foot strap; Foot stretcher cover) allow to locate the feet in the right position through the regulation of the control factor h (see, e.g. Fig. 5). Thus, to avoid part displacements, we fixed the rear part of the ergometer with the cuboid base using a strong commercial plastic crimp band and we weighted down components and experimental support with a stabilizing mass of 245 kg (see middle part of Fig. 6).

Table 1 Adjustable factors and their levels selected for the development of the design of experiments

Factors	Level 0	1	2
I: *Interaxle spacing feet*	I_s	I_c	–
α: *Foot angle*	0°	10°	20°

To find the relevant ballast value we asked to every rower to make five strokes at maximum power (maximum strokes per minute and maximum force). In this way, we can work in safe and stable conditions since the tests were carried out by each rower at thirty strokes per minute.

4 Validation

In this section the design evaluation and validation are described. The whole process starts with the definition of the two experimental configurations. Then, the experimental phase is illustrated in detail. Finally, performance based analysis and an user study are described, applied and discussed.

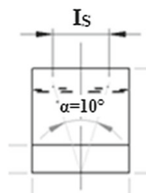
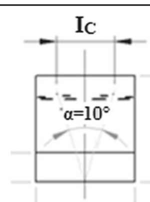
4.1 Experimental treatments definition

For the definition of the experimental treatments, we start by translating each variable parameter of the NAIF into adjustable factors, which are I and α (see Table 1). We set the first factor on two levels, the first with I equal to 205 mm (I_s) and the second level customized with the athlete's anthropometrical characteristics (I_c). Indeed, the second factor is set on three levels according to the possible allowed foot angles (0° as level 0, 10° as level 1, and 20° as level 2). Based on the opinion of the rowing experts, in order to reduce the number of run-tests (to avoid the effect of fatigue) and, at the same time, to collect an adequate number of data, we set the factor on the level 1 (10°). So, the treatments in the Table 2 are chosen for the experimental phase.

4.2 Experimental setup

Eight rower volunteers (male, Italian) participated at the experimental session. Participants signed a written informed

Table 2 Mixed Factorial plane of two factors consists of six types of experimental foot stretcher set-up

Treatment	I	α	Experimental set-up
1	0	1	
2	1	1	

consent, in accordance with Ethics Committee of the University of Naples Federico II. They have different anthropometric characteristics, which cover a large range of the rowing population. In according to their competitions and results in last two years, the athletes are divided into two categories, one belonging to the rower's hand side (four right and four left) and one belonging to the different competitive levels (three international, three national and two regional). The participants had not suffered severe injuries in the last twelve months before the testing day. One physician collected the informed consent from volunteers as well as their personal details (i.e. age and type of rower) and anthropometric characteristics (i.e. pelvis width and weight). Table 3 shows all data recorded with μ (mean) and σ (standard deviation).
The experimental activity was carried out at ErgoS Lab, the Laboratory of Advanced Measures on Ergonomics and Shapes placed at CESMA of the University of Naples Federico II. The Model C Concept2 rowing ergometer and NAIF were used to perform the experimental phase. The evaluation of the novel adjustable foot stretcher has been conducted with two different inter-axle settings according to the output of the study in the previous paragraph. The first (treatment 2) with the standard value (standard inter-axle spacing feet I_s = 205 mm), the second one (treatment 5) equal to the distance between the hip joint centres: in according with Seidel et al. [23], it was defined as the 72% of the athletes width pelvis (custom inter-axle spacing feet I_c, see Table 3). The regulation of the foot stretcher along the s-direction (see e.g. Fig. 2) was adjusted by rowers in accordance to their perception. Data from the tests were collected through two instruments. First, the power transmission data were collected from the ergometer.

Second, the body pressure on the sliding seat was measured through a body pressure mapping system made of resistive mats (Body Pressure Measurement System from Teskan), at sampling frequency of 10 Hz. The pressure area of system have a squared shaped composed by 32 × 32 cells (the single squared cell has an area of a = 217 mm^2). For each rower, before the first experimental run-test, the leader performed the calibration process of body-pressure system. In order to allow a better pressure data acquisition, we fixed a specific rigid support around the carrel. The mats were fixed through laces in the holes of the rigid support. The rowers performed a warm-up of ten minutes before the first run-test. The protocol study consists of two sessions with three run-tests of fifteen strokes with a fixed stroke rate (standard stroke rate ρ_s = 30 stroke/min) and drug (one-hundred-twenty-five). Figure 7 shows a photo-sequence of a rowing run test. Each participant performed one session for each configuration of NAIF. The run-test order of each session was randomized. The run-test can be divided in three parts: (i) initialization phase, from the first to the fourth stroke; (ii) test phase, from the fifth to the fourteenth stroke; (iii) recovery phase composed by the last stroke.

By means of the ergometer screen, the athlete controlled the performance and tried to keep a constant stroke rate during the test. The real stroke rate ρ_r was evaluated through the coefficient $\epsilon = \rho_r/\rho_s$ Run-tests with a coefficient ϵ over ± 3%, in the test phase were excluded from the evaluation. The time period was three minutes between the run-tests and seven minutes between the two sessions. The goal was to provide the athletes an adequate rest for muscle recovery and to allow the assessment of improvements or worsening between different settings. At the end of the two sessions, the test leader collected user feelings through a specific questionnaire. The participants involved in the study were asked to fill an online-based survey with the objective to rank the enhanced ergometer with respect to the standard one. For this evaluation, we choose two evaluation criteria with the help of a trainer, the power transmission and the comfort.

4.3 Performance-based analysis

For the body pressure row data, we applied a moving average filter with a windows size equal to four. From the filtered data, the processing started with the calculation of the load on the sliding seat L (N/mm^2):

$$L(t) = \sum_{i=0}^{n} l_i(t) \tag{1}$$

where n is the number of the loaded cell for each instant of samples and $l_i(t)$ is the load applied on each cell of the body pressure mapping system. Indeed, the pressure area A (mm^2) is computed from the area cell a as:

$$A(t) = n(t) \cdot a \tag{2}$$

Table 3 Competition level, hand side, age, stature, weight pelvis width and interaxle spacing feet related to the pelvis width (I_c) of the rowers

Rower	Level	Side	Age (year)	Stature (mm)	Weight (kg)	Pelvis width (mm)	I_c (mm)
1	Regional	Left	30.9	1800	75.6	250	180
2	Regional	Right	24.4	1800	72.3	256	184
3	National	Right	23.0	1700	75.0	262	189
4	National	Left	22.0	1800	97.2	268	193
5	National	Left	22.0	1790	74.8	250	180
6	International	Right	26.1	1930	95.9	300	216
7	International	Right	28.6	1960	95.0	268	193
8	International	Left	17.8	1760	66.6	245	176
Mean	–	–	24.7	1818	81.6	262	189
σ	–	–	4.0	86	12.3	17	13

In the last two lines mean and standard deviation σ related to previous list of data are shown

Fig. 7 Three main highlights of a rowing run-test: (left) the catch event; (middle) the instant of minimum load on the sliding seat; (right) the finish event

The expression of the load L as function of the body weight force bw of the athletes yields the adimensional parameter L_{bw} (%) as:

$$L_{bw}(t) = \frac{L(t)}{bw} \cdot A(t) \cdot 100 \tag{3}$$

Then, we found the set of the instants $t(L_{min_i})$, where L_{bw} has a relative minimum L_{min_i}:

$$\begin{cases} \{t(L_{min_i})\} = \{\min L_{bw}\} \\ L_{bw} \leq 30\% \end{cases} \qquad i = 1, \ldots, 16 \tag{4}$$

where the subscript i represents the sequential number of the minimums during the test. In the following, in order to evaluate the stroke rate ρ_r during the test phase, we define, for each stroke j, the set of stroke time t_j and the set of stroke rate f_j. These values are evaluated between the fifth and the fifteenth minimum one (i.e., during the test phase):

$$\begin{cases} \{t_j\} = \{(t(L_{min_i}) - t(L_{min_i - 1}))\} \\ f_j = \frac{1}{t_j} & i = 6, \ldots, 15 \\ \rho_r = \frac{\sum_{j=1}^{10} f_j}{10} & j = 1, \ldots, 10 \end{cases} \tag{5}$$

Finally, the t_j has been normalized in order to achieve a percentage of the stroke rate (Cycle %) in the range between 0 and 100 (Fig. 8 top part). In the following, we derive an average load index which relates sink and disequilibrium. In order to quantify the sink, we consider the following parameter α as:

$$\begin{cases} \alpha(t) = \left(\frac{L_{bw}(t)}{L_{max}}\right) \\ L_{max} = \max\{L^r_{bw}(t)\} \end{cases} \tag{6}$$

where the superscript r indicates the number of rower, $L^r_{bw}(t)$ represents all load values during the cycle express in body weight for the rower, and L_{max} is the maximum value of $L_{bw}(t)$ measured during the cycle between overall tests. Furthermore,in order to quantify the disequilibrium, we divided the area of the mat into two equal parts and define the auxiliary variable γ:

$$\gamma(t) = L^{dx}_{bw}(t) - L^{sx}_{bw}(t) \tag{7}$$

where $L^{dx}_{bw}(t)$ and $L^{sx}_{bw}(t)$ represent load values during the rowing cycle espress in body weight for the right (dx) and left (sx) side (Fig. 8 bottom part). Finally, the definition of following parametr β allows to quantify the disequilibrum:

$$\begin{cases} \beta(t) = \left(\frac{\gamma(t)}{\gamma_{max}}\right) \\ \gamma_{max} = \max\{\gamma^r_{max}(t)\} \end{cases} \tag{8}$$

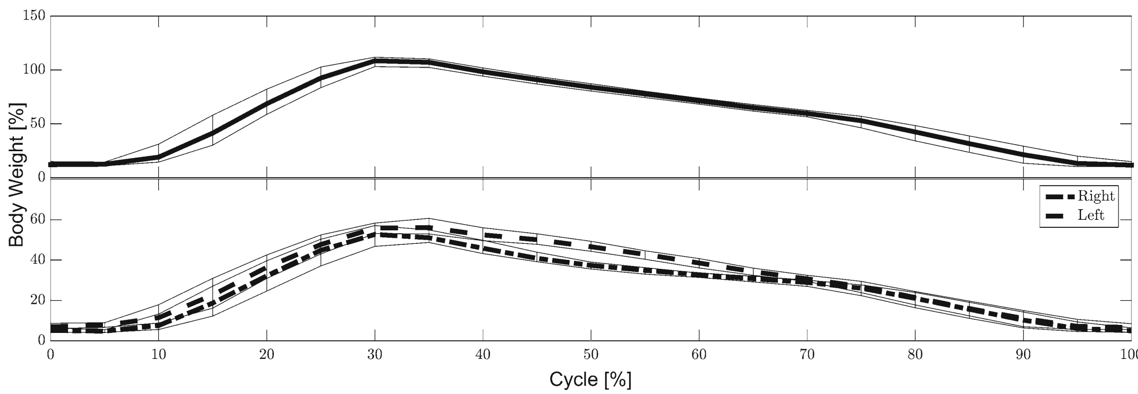


Fig. 8 The top figure shows the L_{bw} as function of the cycle (%). The black bold line indicates the average values taken on the ten stroke times during the test phase while vertical bars the standard deviations. The bottom figure shows the L^{dx}_{bw} and L^{sx}_{bw} as function of the cycle (%). The dash-dot line indicates the average taken on the ten stroke times during the test phase for the right side while vertical bars associated the standard deviation. The dashed line indicates the average taken on the ten stroke times during the test phase for the left side while vertical bars associated the standard deviation

where the superscript r indicates the number of rower, and γ_{max} is the maximum absolute value of different between sides measured during the cycle (expressed in body weight) between the overall tests. Finally, the desiderate average index is defined as:

$$\mu_m = \alpha_m \cdot \beta_m \tag{9}$$

where α_m and β_m represent respectively the average values of (6) and (8). All parameters were included between 0 and 1. The value 0 represented the best situation, while the worst event occurred if the parameter is equal to 1. For the body power transmission data (PTD), collected by ergometer, we evaluated for the two configurations the mean value in the test phase of the ratio power index κ_m (W/ N) through following equation:

$$\kappa_m = \frac{\sum_{j=1}^{10} PTD_j}{10} \cdot \frac{1}{bw} \tag{10}$$

where the subscript j represents the number of stroke in test phase. In this case, higher scores represent the best performance, while the score 0 is the worst situation.

4.4 User study

The study conducted on the rowers has the objective to further evaluate the enhanced ergometer with respect to the standard one, from an end-user perspective. The rowers performed two training sessions, using the same ergometer, one with NAIF in standard configuration, one with NAIF in customized configuration. The first configuration resembles the standard foot stretchers, while the second allows the regulation of I and α, besides the regulation along the s-direction. Two evaluation criteria have been selected, the comfort (Co) and the power transmission (PT) feelings, both from the users side. Therefore, the scenario consists of two configurations to be evaluated according to two criteria. This problem can be approached from a decision science point of view. Indeed, multiple criteria decision making processes might generate the ranking of the configurations with respect to the different criteria, leading to an optimal solution. Among these methods, the fuzzy AHP is an elegant way to address problems with alternatives belonging to a discrete set, as the current scenario. A recent implementation of fuzzy AHP which led to a distributed framework called ELIGERE might be used in this phase to help design teams in evaluating design solutions from an end-user perspective. The eight rowers were asked to fill a web-based questionnaires divided in two parts: (i) preference section, consisting in a comparison about criteria; (ii) suitability section, consisting in a comparison about alternatives with respect to each criterion separately. The output of (i) is the ranking of the criteria, while the output of (ii) is the ranking of the configurations, obtained after the aggregation of all the answers according to the fuzzy AHP methodology.

4.5 Results and discussion

The pressure and power transmission data collected in the experimental phase are processed with performance evaluation method (cf. Sect. 4.3) and the indexes obtained are shown in Table 4 (for each athlete is shown the mean value of the indices between the three run-tests). The multiple criteria decision-making method through the ELIGERE framework (cf. Sect. 4.4) carried out: (i) the score of criteria in the two configurations; (ii) the ranking of criteria; (iii) the ranking of configurations (see Fig. 9). Table 5 shows the effect of the enhanced configuration in comparison to the standard one

Table 4 Pressure and power indices (best values for each index are underlined for all rowers)

Rower	Level	Side	Pressure						Power	
			α_m^S	α_m^E	β_m^S	β_m^E	μ_m^S	μ_m^E	κ_m^S	κ_m^E
1	Regional	Left	0.380	0.373	0.242	0.221	0.092	0.082	0.584	0.597
2	Regional	Right	0.463	0.454	0.105	0.091	0.049	0.041	0.622	0.610
3	National	Right	0.432	0.381	0.328	0.298	0.142	0.114	0.585	0.603
4	National	Left	0.543	0.538	0.076	0.108	0.041	0.058	0.460	0.469
5	National	Left	0.453	0.441	0.088	0.062	0.040	0.027	0.632	0.639
6	International	Right	0.490	0.455*	0.242	0.122*	0.119	0.056*	0.520	0.607*
7	International	Right	0.453	0.441	0.088	0.062	0.040	0.027	0.554	0.587
8	International	Left	0.466	0.454	0.037	0.078	0.017	0.035	0.590	0.567
Mean	–	–	0.460	0.442	0.151	0.130	0.067	0.055	0.568	0.585
σ	–	–	0.046	0.051	0.105	0.085	0.044	0.030	0.056	0.051

The * specifies indices with significant differences ($p < 0.05$). The superscript S and E indicate respectively the standard configuration and enhanced one

Table 5 Mean effect of the enhanced configuration related to quantitative performances indices and user study one

Performance indices				User study indices	
Pressure			Power	Comfort	Power
$\Delta\alpha_m$	$\Delta\beta_m$	$\Delta\mu_m$	$\Delta\kappa_m$	ΔCo	ΔPT
+4%	+14%	+18%	+3%	+18%	+46%

related to the performances indices and user study analysis. For performance indices these effects are evaluated through the difference between the two configurations score divided with the standard score. The results of user study (see Fig. 9 and Table 5) confirm the output of performance-based analysis. Indeed, the ranking of the configuration underline how the enhanced configuration responds better than standard one at the athletes need (with a score improvement of 32%). Furthermore, Table 6 shows a notable improvement of the score for all criteria (+ 46% for Power Transmission (PT) and + 18% for Comfort (Co). We can underline that the improvements of these indices are greater than performances analysis. Finally, the relevance of the criteria appears similar. Indeed, the scores of criteria are very close to each others with 52% for the Power Transmission (PT) versus 48% for the Comfort (Co). The performance results are also evaluated through statistical analysis. The differences between the configurations and between the groups are evaluated by paired Students test (with $p < 0.05$) after verifying the normality with the Anderson–Darlings test ($p < 0.05$). Significant differences are emerged only for one athlete (see Table 4), in particular, for the only case in which the enhanced configuration presents an interaxle value larger than the standard one 216 versus 205 mm, see Table 3. Although, the group analysis (see Table 6) confirms the improvements for all indices with the enhanced configuration, no significant differences are emerged between the groups.

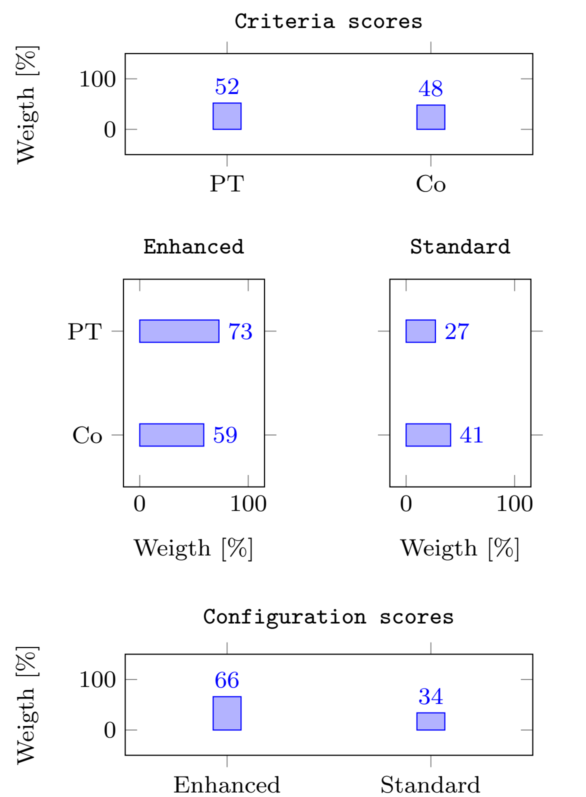


Fig. 9 ELIGERE output: (top) the score of the criteria; (middle-left) the score of the enhanced configuration w.r.t criteria separately; (middle-right) the score of the standard configuration w.r.t. criteria separately; (bottom) the final ranking of the configurations

5 Concluding remarks

In this paper we proposed the design of a Novel Adjustable Inter-axle Foot stretcher. We approached the design process using a participatory approach, in the sense that the end-users of the product were directly involved into the whole design

Table 6 Pressure and power indices for each group of competition level: regional, national and international

Group	Pressure									Power		
	α_m^S	α_m^E	$\Delta\alpha_m$ (%)	β_m^S	β_m^E	$\Delta\beta_m$ (%)	μ_m^S	μ_m^E	$\Delta\mu_m$ (%)	κ_m^S	κ_m^E	$\Delta\kappa_m$ (%)
Regional	0.422	0.414	+2	0.174	0.156	+10	0.070	0.062	+12	0.603	0.604	+0
National	0.476	0.453	+5	0.164	0.156	+5	0.074	0.066	+11	0.559	0.570	+2
International	0.470	0.450	+4	0.122	0.087	+29	0.059	0.039	+33	0.555	0.587	+6

The best values are underlined for each group. The *specifies values with significant differences. The superscript S and E indicate respectively the standard configuration and enhanced one

process, from the conceptual design until the design evaluation and validation. We started the design from the needs related to the different anthropometric characteristic rowers' population. With their help and the help of the rowing experts, we select two design factors and two design configurations. We validated the design using a performance-based evaluation including four performance indices: three related to the body pressure: (i) α, in order to quantify the sink; (ii) β, in order to quantify the disequilibrium; (iii) μ, in order to have an average index for body pressure; and one related to power transmission, κ, in order to consider the power transmission in relationship with the body weight. With the NAIF, we improve the athletes performance by 4% for α, 14% for β, 18% for μ and 3% for κ. A statistical analysis based on paired Student's test underline that these improvements are significant for athletes which required (according to their anthropometrical characteristics) an inter-axle spacing foot larger than the standard one. Finally, a user study on the athlete involved in the tests, further enforce the improvements of the enhanced respect to the standard one (+ 32% of alternative score) and respect to the comfort and power transmission feeling respectively by 47% for the Power Transmission and 18% for the Comfort. In conclusion, the study demonstrates that the proposed methodological approach, based on participatory design of a novel foot stretcher, offers a useful tool to improve the indoor rowing training. Further developments will be centred on: (i) a new experimental phase to study the effect of the foot angle parameter (α) on the response of the system; (ii) new tests with female athletes that have different anthropometrical characteristic related to the pelvis width.

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