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HUMAN POWER; COMFORTABLE ONE-HAND CRANKING

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Abstract

Research into ergonomics is one of the aspects in the research for human-powered energy systems. In this specific field, data on maximum force exertion and endurance can be found in a large number of publications, mainly originating from sport or military related research. Data on comfortable or sustainable force exertion however prove not to be available. In this research project we attempted to measure comfortable/sustainable force exertion. We mapped one specific movement (one-handed cranking) using the Critical Power test. This test is based on the assumed linear relation between maximal work and time to exhaustion (Morton's 3-parameter critical power model). The experimental set-up consisted of an altered cycle-ergometer which was adjustable in height. We measured the subjects' (eight young males) maximum power output and the time to exhaustion at different power levels. The research showed a sustained power output from cranking to be: 54 ± 14 Watt (mean ± SD). In the paper we will present the research project and its results and link them to literature in the field of comfort.

Keywords: critical power test, comfort, human power

1. Introduction

1.1 Why human-powered products?

Nowadays we see a growing number of portable electric consumer products, mainly powered by batteries. Examples are; audiovisual, communication and information products, in which the electronics provide the main functionality, but also an increasing number of products that deliver mechanical work at their output. Considering the clear advantages of rechargeable batteries (high energy density, wide availability and international standardization), they will remain the main source of power in the forthcoming period. Nevertheless, the use of batteries can be cumbersome as well. Batteries run out of energy when you need them most, they're not always available, they have to be replaced or charged in a troublesome way and in the long run batteries turn out to be a rather expensive power source. Moreover, due to the increasing number of battery-powered portable products, the environmental impact of battery use might increase as well. Driven by consumer perception and environmental concern, the Personal Energy System (PES) group at DUT aims at finding alternatives for the increased use of batteries in portable energy products. In this scope the PES-group focuses on the application of renewable energy sources in consumer products. Special emphasis is given to low power

energy sources such as; human power (i.e. the use of human work for energy generation), direct methanol fuel cells, and photovoltaic solar cells.
In this paper we will focus on human power.

In our research project we defined human power as; using the human body as an energy source for electric products. The main advantages of human powered products are; they operate independent of energy infrastructures, have a long “shelf-life” and can be environmentally beneficial in the long run. Some examples of human powered products on the market nowadays can be seen in the next figure.

Figure 1. Some examples of human powered product. From left to right; the Seiko Kinetic watch, the Coleman radio, the Philips AE 1000 radio and the Aladdin Power hand generator

In the research for human power we identified three areas of scientific interest: the environmental impact of human-powered vs. battery-powered products, the engineering of small -but efficient- generators and human factors of power input. This paper will discuss the latest area, specifically one-hand cranking.

1.2 Comfort and measuring comfort

Acceptance of human-powered products, i.e. prolonged and repetitive use of the product, is only possible when discomfort –inevitable associated with the use of these products- can be limited. Definitions of (dis)comfort vary from ”comfort is the subjective positive perception of the nature and intensity of the load, resulting from using or operating an object” [1], “discomfort is the result of bodily pains, arising as a result of the postures and effort involved” [2], “discomfort is a phenomenon of perception, related to pain, fatigue, and perceived exertion”. Discomfort can be divided into short term and long term discomfort [3]. Short term discomfort (our focus) can be measured by rating or ranking the subjects feelings [4] and observing/registering of body posture, movement and force (OWAS and RULA method) [5]. From literature we also concluded that discomfort is associated with pain and fatigue. Kroemer [6] describes a number of methods to determine fatigue. Out of these methods, measuring the output is the most practical way to assess (strain) and fatigue, defined as “…the inability to maintain power output…”[7]. In our research we found one method aimed at measuring sustained force exertion, the Critical Power test. It has been used for the determination of the power output sustained for several hours in synergic muscle groups [8], total body work [9] and several other purposes. The CP-test (critical power test) has been validated by comparing it to the ventilatory threshold and the physical work capacity at fatigue threshold [9].

The CP-test has been used in earlier research [10] on cranking with three trained paraplegic subjects (mean ± SD = 36 ± 9 yrs). In this test, the shoulder was in line with the axis of the ergometer and the wheelchair was placed so the subject's arm was fully extended when the crank handle was at its greatest distance. We suspect this was one-hand cranking although this is not clear from the literature. The power outputs used were 25, 37.5 and 50 W. The test ended immediately when the subject was unable to maintain a cranking rate of 50 RPM. Rest periods between each period of exercise continued until the heart rate returned to a range within 10 BPM of the subject's resting heart rate. Each test was repeated three times in different sessions. Linear regression was expressed by the following equation;

$$W_{\mathrm{lim}} = \mathrm{AWC} + \mathrm{CP}\cdot t_{\mathrm{lim}} \tag{1}$$

W_{lim}	work value [Joule]	AWC	anaerobic work capacity [Joule]
t_{lim}	time to exhaustion [seconds]	CP	critical power [watt]

For subject 1: $W_{\mathrm{lim}} = 5905 + 22\cdot t_{\mathrm{lim}}$, Subject 2: $W_{\mathrm{lim}} = 6384 + 24\cdot t_{\mathrm{lim}}$ and subject 3: $W_{\mathrm{lim}} = 5722 + 21\cdot t_{\mathrm{lim}}$ This means that subject 1 has a Critical Power of 22 W , subject 2 of 24 W and subject 3 of 21 W [10].

2. The Critical Power Test

2.1 Problem statement and research question

In the field of ergonomics, data on (maximum) static and dynamic force exertion and endurance can be found in a large number of publications, mainly originating from sport or military related research. In our search we could not find specific data on 'comfortable' or 'sustainable force exertion', nor standardized measurement methods to determine these values. We assume the critical power test to be the best available alternative. Most estimations on long-term static force exertion are based upon percentages, varying from 15 to 20%, of the maximum strength [6] [11]. We assumed an identical relation between P_{max} and CP in order to estimate the time to exhaustion (t_{lim}).

This leads to the definition of the following research question; is it possible to quantify the "sustainable-comfortable power output" from one-hand cranking, and if so; what is its value and variation for a specified population? [12]

2.2 Materials and methods

Subjects; the subjects in the pilot study (n=2) and the main study (n=8) were healthy young men, age from 19 to 26 years. Materials; we used an adapted bicycle ergometer (Lode RH30) (see figure 2) in which the pedal was replaced by a crank handle (diam. 25 mm, length 95 mm). The crank arm length was 175 mm (fixed). The ergometer was mounted on a hydraulic lift in order to adjust the crank height to fit the subjects' anthropometric measurements. The resistance (power) of the ergometer could be varied in between 5 to 250 watt. The ergometer featured a speedometer (analogue dial in RPM) and an analogue output. The analogue output was connected to a writing recorder (Kipp, BD 41) in order to log the cranking rate.

A photoelectric pulse plethysmograph (Boucke, Infraton Kardio PF100) was used to measure the heart rate (in BPM) every ten seconds during the warm-up, test period and cool-down. We used a video camera to record the tests. Time was measured using a hand-held stopwatch.

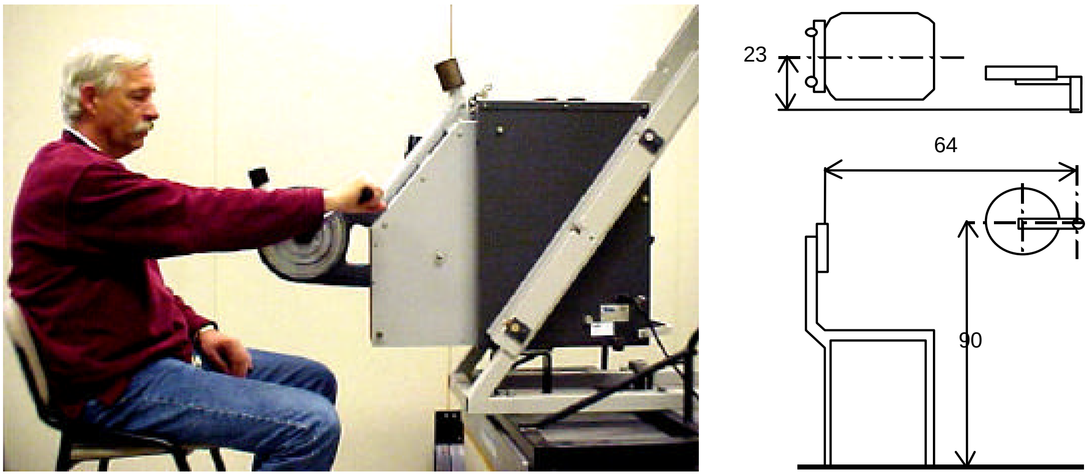

Figure 2. Measurement set-up (altered ergometer) and relevant anthropometric values (NB no research subject)

Test procedure; The arm cranking ergometer (see figure 2.) was secured to a hydraulic lift in order to keep the heart in line with the crank axis. The subject was seated in a normal chair so the subject's arm was almost fully extended when the crank handle was at its greatest distance. A speedometer was observed by the subject to maintain the prescribed cranking rate (60 RPM) throughout the test. Cranking rate was recorded continuously and the heart rate was measured at 10-s intervals using a photoelectric pulse plethysmograph. The main test was preceded by a pilot study in order to gain more insight in a number of variables. Here we learned the initial instruction “stop cranking if you feel pain or when cranking becomes uncomfortable” proved to be to vague. It was altered into “keep cranking until you’re unable to maintain the cranking rate of 60 RPM”. All tests were preceded by a 2-min warm-up at 5 W, with increasing cranking rate until 60 RPM and followed by a 2-min cool-down at 5 W. Not more than two tests on one day, with a rest period of at least three hours between tests.

2.3 Measurements protocols

Protocol CP-test; The subjects performed three tests in which the power output remained constant and led to the onset of muscle fatigue. The appropriate power output was set within 2-3 s. The moment the power output was set, the stopwatch and recorder were activated. The test was ended when it lasted longer than 30 minutes or in case the constant power output level could no longer be sustained (i.e. cranking rate drops below 55 rpm, determined by the written output from the recorder.

Protocol for maximal power output (P_{max}); The initial power output was set to 5 W, after 10 seconds an increase of 5 W and subsequent increases of 10 W every 10 seconds. The test ended when the constant power output level could no longer be sustained, i.e. a drop in cranking rate below 55 rpm (determined by the written output from the recorder). The test was followed by a 2-min cool-down at 5 W. The P_{max}-test was done twice: one before and one after the Critical Power Test.

Protocol comfort test; The CP was validated by a comfort test. The appropriate power output was set within 2-3 s after starting to crank, then the stopwatch and recorder were activated. Every two minutes the subject gave his rating for the perceived exertion. The test was ended after 30 minutes; or when the constant power output level could no longer be sustained, i.e. a drop in cranking rate below 55 rpm. The comfort test was done once.

2.4 Results main study

The results of the study consist of; P_{max}, P_{max} at re-test, W_{lim} (according to Morton's 3-parameter critical power model [13]) and the comfort test (rating perceived exertion at Borg scale [4]).

Table 1. Results of main study

Subject	P_{max} [watt]	$P_{max\ re\text{-}test}$ [watt]	W_{lim} $(=AWC + CP.t_{lim})$ [Joule]
A	118	129 (+9%)	$4655 + 35\ t_{lim}$
B	119	157 (+32%)	$5053 + 55\ t_{lim}$
C	142	141 (1%)	$3257 + 78\ t_{lim}$
D	109	120 (+10%)	$8249 + 50\ t_{lim}$
E	139	159 (+14%)	$12.596 + 54\ t_{lim}$
F	128	168 (+31%)	$5096 + 51\ t_{lim}$
Main	126	146 (+16%)	-

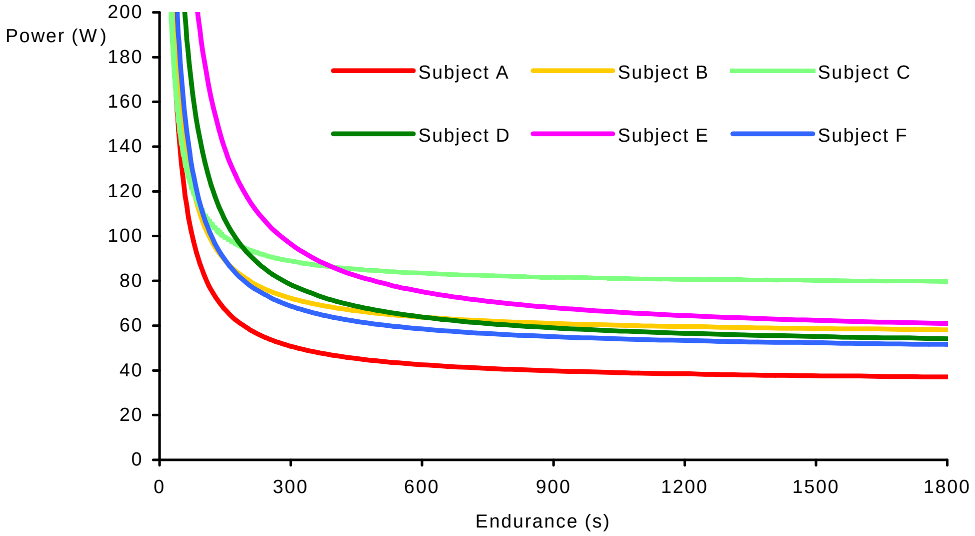

Figure 3. Endurance

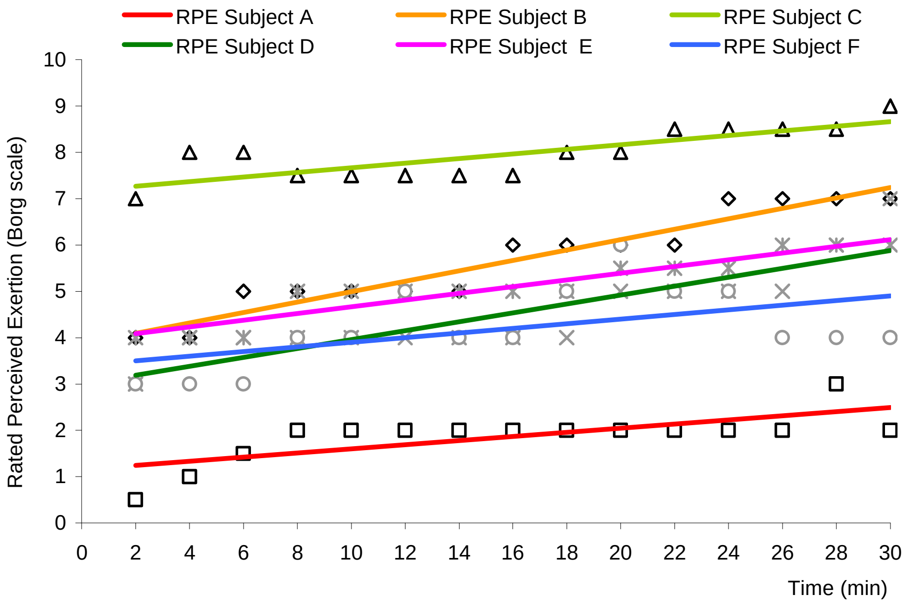

Figure 4. Rated perceived exhaustion (Borg scale) during comfort test

2.5 Discussion and conclusion

Subject A has a CP that is much lower than the CP of the other five main study subjects. A possible reason for this low CP is the relative high heart rate at rest of up to 85 BPM, where 60-70 BPM is normal. The heart rate appears to be a good indicator of the relative load, in a homogenous age group. Therefore, the workload is relatively higher for subject A than for the other subjects. Subject C has a very high CP; the probable reason is that he is a real sportsman. He played premier league field hockey for a couple of years. His oxygen uptake was tested very high; hence he can sustain a very high aerobic work level.

The CP is assumed to have a normal distribution; the standard deviation can be measured for the main study subjects: mean ± SD: 54 ± 14 W. The sustained comfortable power output for 95% of the population: mean – 1.65 ·SD = 54 – 1.65 · 14 = 31 W.

P_{max} is a inaccurate predictor of t_{lim}. Subject C cranked for 30 minutes at 56% of his P_{max}, without exhaustion, while subject A cranked at 42% of his P_{max} for only 5 minutes and 13 seconds. The difference between P_{max} before and after the Critical Power tests indicates a familiarization effect. Subject B and F had a large difference between P_{max} before and P_{max} after respectively 32 and 33%. For subject B and F we found that the linear regression was not equal to the non-linear regression. The linear regression became equal to the non-linear regression after skipping the power outputs with a large difference between test and retest.

All the subjects cranked for 30 minutes at their CP. Subject A (with a low CP) rated his perceived exertion as maximal 3 (moderate according to the Borg scale). His maximal heart rate during the comfort test was 120 BPM, So he could probably have continued cranking for a very long time. The RPE of subject F decreased after 20 minutes from 6 to 5, and even to 4 at 30 minutes. He too could probably have continued cranking for a very long time. On the other hand, subject C with a high CP rated his maximal perceived exertion as 9, almost extremely strong according to the Borg scale. His heart rate reached 155 BPM. He would probably have stopped cranking in a few minutes, because his perceived exertion would have reached the maximum. For subject C the CP might be overestimated, this is not unlikely because his CP of 78 W is at least 50% higher than the other subject's CP.

Aminoff et al. [14] concluded that even a low level of arm work seemed to contribute to a continuous increase in both circulatory (heart rate) and subjective responses (RPE). They concluded that arm work always should be adjusted with adequate rest pauses. Therefore, it cannot be concluded that because the critical power was sustained for 30 minutes, it will be sustained without exhaustion for hours. On the other hand, cranking for 30 minutes at 54 W delivers almost 97 kJ. In theory, this amount of energy (- 50% conversion efficiency), suffices to power a Motorola 130 (0,72 W) cell phone for 19 hours or to run a 6 W video-8 camera for 2 hours and 15 minutes.

From this research project we concluded it is possible to 'quantify sustained one-hand cranking' for a specific group of subjects, in this case young males. When precise readers see this conclusion, they may have missed the word 'comfortable' here. It is left out deliberately because we realized we only measured "the ability to maintain power output" (see definition in § 1.2). According to literature this is one dimension of comfort or discomfort only. So, the second conclusion is that the CP-test is not an unabridged device for measuring comfort or discomfort. Therefore, the next chapter will elaborate on the relation between human power and comfort.

3 Human power and comfort

3.1 (Dis)comfort and motivation

Vink [15] describes a number of notions concerning comfort: it is influenced by many factors in the environment, it's exact cause is unknown nor modeled, it is a subjective phenomenon and the design approach towards comfortable products is unknown. Three conditions or manifestations of comfort are distinguished;

- Discomfort: the participant experiences discomfort because of physical disturbances in the environment
- No discomfort: the participant is not aware of the fact that there is no discomfort (mind: absence of discomfort is not equal to 'comfort')
- Comfort: the participant experiences noticeably more comfort than expected (related to luxury, relaxation and refreshment) and feels comfortable

In the comfort model by Vink [15] (see figure 5), the input consists of external stimuli (sight, smell, noise, pressure, etc..) and internal stimuli (history of comfort experience and state). The output consists of: comfort, no discomfort and discomfort.

Making a human-powered product is a deliberate action to introduce a certain amount of discomfort in the product. The amount of 'added discomfort' is, among other things, proportional with the power required to drive the product. This can be 'near zero' (self powered watch) to a considerable amount (hand-squeezed torch). Depending on the users' motivation to use the product he or she will choose to accept or reject this 'added discomfort' for a certain period.

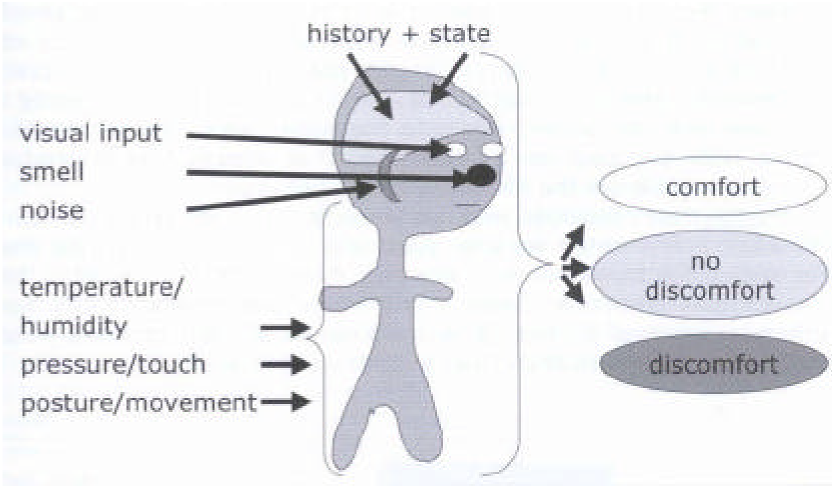

Figure 5. comfort model by Vink [15]

In literature a number of definitions of ‘motivation’ can be found. Here I will use an adapted definition by Hunger; “motivation is a set of forces within a person (either intrinsic or extrinsic) that arouse direction (what), intensity (how hard) and persistence (how long)”. These forces are partly determined by Maslow’s hierarchy of needs: ‘a person will be motivated by a particular level of needs until that need is satisfied, then he will be motivated by the next higher level of needs’. Measuring motivation is difficult, as it is indirect. From [16] we learn that we do not see motivation, but behavior.

Now, compare these two cases:

- My sailing boat just sunk to the bottom of the ocean. I’m on board of a life raft cranking-up the emergency radio generator.
- I’m sitting on the couch watching a boring TV-show. I’m cranking-up my remote control in order to change channel.

From these two cases it is obvious there will be a large difference in motivation and thus in the acceptance of ‘added discomfort’.

I will now propose a model describing the acceptance of added discomfort in human powered products (see figure 6). The input consists of both the users’ motivation, based on perceived needs and the perception of discomfort (as output from Vinks’ model, see figure 5). The output consists of accepting or rejecting discomfort and therefore the human powered product.

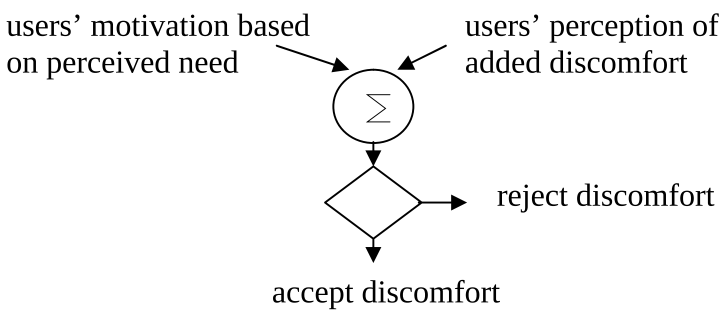

Figure 6. Model describing the acceptance of added discomfort.

Once the user experiences discomfort in using a human-powered products, he might consider how this discomfort compares to his perceived need and accept the discomfort or reject the use of the product. Accepting a certain amount of added discomfort will be product related, i.e. the factor df/dd in the figure below will be different for various products. For example products A, B or C.

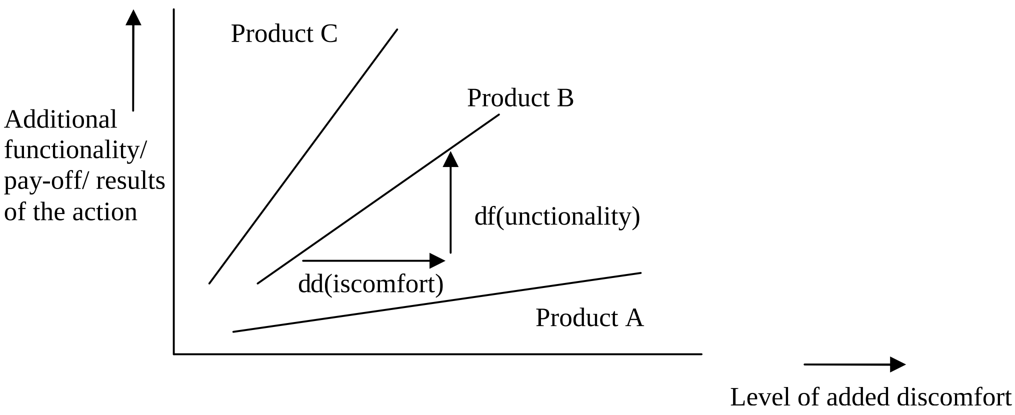

Figure 7. Additional functionality vs. level of added discomfort

3.2 Conclusions

In the CP-test as described, the motivation of the subjects seemed to consist largely out of ‘not wanting to disappoint the researcher’. However valid the measurements might be, they are not valid in situations where there is a different motivation. The example presented in the two cases gives a good impression of the magnitude of possible differences.

The proposed model on the acceptance of added discomfort will have to be tested. Tests on sustainable force exertion should either eliminate the influence of motivation (not realistic) or test the sustainable force exertion at different levels of motivation. These questions pose a new challenge for the research in the field of human powered products.

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