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Original
Estimation of Force Effectiveness and Symmetry During Kranking Training / Digo, E.; Gastaldi, L.; Antonelli, M.; Cornagliotto, V.; Pastorelli, S.. - 108:(2022), pp. 201-208. (Intervento presentato al convegno 1st Workshop IFToMM for Sustainable Development Goals, I4SDG 2021 nel 2021) [10.1007/978-3-030-87383-7_22].

Availability:
This version is available at: 11583/2943572 since: 2021-12-08T15:10:42Z

Publisher:
Springer

Published
DOI:10.1007/978-3-030-87383-7_22

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This is a post-peer-review, pre-copyedit version of a book chapter published in Mechanisms and Machine Science. The final authenticated version is available online at: http://dx.doi.org/10.1007/978-3-030-87383-7_22

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03 December 2023

Estimation of force effectiveness and symmetry during kranking training

Elisa Digo[1], Laura Gastaldi[2], Mattia Antonelli[1], Valerio Cornagliotto[1], Stefano Pastorelli[1]

[1] Dept. of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy
[2] Dept. of Mathematical Sciences “G.L. Lagrange”, Politecnico di Torino, Turin, Italy
`elisa.digo@polito.it`

Abstract. The third Sustainable Development Goal of the 2030 Agenda promotes healthy lives and well-being for all people of all ages. A good way to ensure a healthy lifestyle is to perform daily physical activity. Among different exercises of cardiovascular training, kranking is a program that involves arm-cranking gesture performed on a stationary handbike. In order to correctly perform this activity, biomechanical parameters have to be monitored. The present pilot study aimed at developing a setup for the quantitative evaluation of the force effectiveness and symmetry during different conditions of upper limbs kranking. One healthy young subject performed different tasks of steady-state cycling on varying cadence, braking torque, and motion pattern. Strain gauges positioned on the handles of a commercial arm-cranking machine allowed the estimation of total and effective forces applied by the user. Moreover, an optical motion capture system was adopted to evaluate the kinematics of the upper limbs during the movement. Comparing the total and the effective forces, the effectiveness of the gesture was evaluated for all testing conditions. Overall, results suggest that the developed setup is adequate to efficaciously identify possible alterations of performance parameters during upper limbs kranking.

Keywords: SDG3, kranking, upper limbs, physical training, active ageing, inclusive fitness

1 Introduction

In line with the third Sustainable Development Goal (SDG3) of the 2030 Agenda, the assurance of healthy lives and the promotion of well-being play key roles for all people of all ages [1]. In this context, physical activity provides many benefits to the health condition. Among different training programs, kranking represents a suitable alternative to the most common physical exercises. Indeed, this stationary form of cycling powered by upper limbs has lots of advantages in different fields such as athletic training, physical therapy, active ageing, and inclusive fitness. More in detail, kranking helps the strengthening of upper body muscles, the increase of workout endurance, and the enhancement of cardiovascular conditions. Hence, many sports activities that involve upper limbs may be attributed to handcycling exercise [2, 3]. In a clinical context, repetitive movements typical of kranking favour rehabilitation and physical therapy in terms of motor learning, functional recovery, and movement coordination [4–6]. The consistent functional consequences of ageing make the elderly health condition a social issue to cope with. Accordingly, kranking might be adopted to improve mobility, balance, and postural stability of healthy elderly people [7]. Finally, handbikes have also become increasingly popular in sports, recreation, and outdoor transportation of people with lower limb impairments [8].

The biomechanical study of the arm-cranking movement from different perspectives can offer concrete help in enhancing performance during physical training. First, the kranking gesture can be analyzed evaluating the benefits on performance of the in phase (the two handles are moved to keep them paired) and antiphase (the movement of one handle has a phase of 180 degrees with respect to the other handle) cycling patterns of motion [9, 10]. Then, starting from biomechanical musculoskeletal models of the human upper body [11], the kranking gesture can be studied considering the involvement of different muscles and identifying push and pull phases in a cycling period [12–14]. Moreover, the analysis may focus on the impact of extrinsic biofeedbacks displaying the performance metrics of work, speed, and cadence during the exercise [15, 16]. Finally, the investigation of the arm-cranking gesture can also concentrate on forces, torques, powers, and cadences at stake [17–19].

The aim of the present pilot study was to validate the tuned setup for the quantitative evaluation of the force effectiveness and symmetry during different conditions of upper limbs kranking. In detail, one healthy and young subject with no experience in hand cycling performed both in phase and antiphase steady-state cycling changing cadence, braking torque, and motion pattern. Strain gauges were positioned on the handles of a commercial arm-cranking machine to estimate the total and effective forces applied by the user. An optical motion capture system consisting of cameras and markers was adopted to evaluate the kinematics of the upper limbs during the movement. Relating total and effective forces, the effectiveness of the gesture was assessed.

2 Materials and methods

2.1 Instruments

The testing activity involved a Krankcycle® machine (Matrix, JHT ITALIA s.p.a.), which is a stationary handbike with independent crank handles, designed for the training of a subject. The power exerted by the user is dissipated by a brake acting on a flywheel. The resistant torque of the brake can be manually adjusted through a knob on the front part of the device. The advantage offered by two independent crank handles allows the reproduction of both in phase and antiphase cycling. In the former pattern the cranks are aligned, while in the latter pattern the cranks are turned in a diametrically opposite position (Fig. 1A).

Two strain gauge sensors were placed on the pins connecting the grips with the crank handles to evaluate the radial forces exerted by the user on each handle (Fig. 1B). Each sensor was made up of four extensometers (HBM, Germany) with electric resistance type 1-LY11-0.6/120. A control unit Spider8 (HBM, Germany) with a built-in conditioning unit was adopted to convert the analogic inputs into digital signals which were processed exploiting the software Catman Easy.

A stereophotogrammetric system with two high-speed cameras was installed in the testing laboratory. Each camera was oriented with the lens orthogonal to the sagittal plane to record both sides of the Krankcycle. The cameras frame rate was set to 100 fps, thus ensuring a proper reconstruction of the cycling gesture, taking place at a comfortable self-selected rate up to 2 Hz [8]. Cameras were calibrated before and after trials using a dedicated calibration tool. Since the cranking movement can be approximately considered planar, a simplified 2D biomechanical model of the upper limbs, based on six markers per side, was adopted. Markers were arranged on the wrists, elbows, shoulders, and acromions of the participant. Two additional markers were fixed on the extremities of each grip to evaluate its instantaneous position and orientation (Fig. 1C).

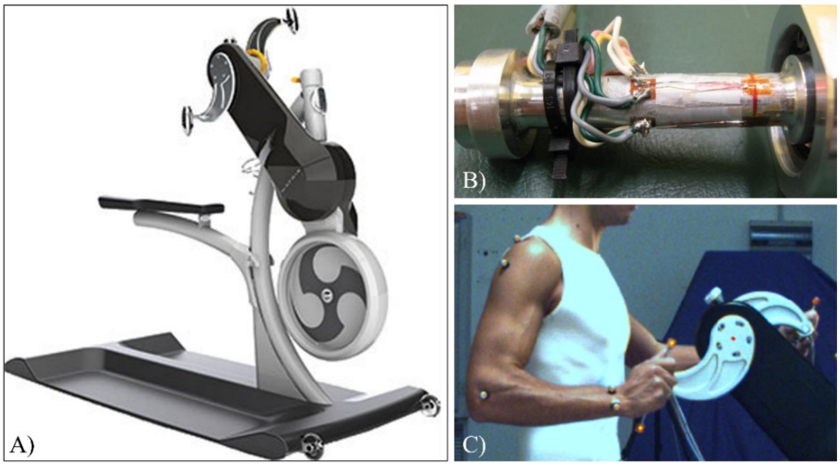

Fig. 1. A) The Krankcycle® machine. B) Strain gauges installed on the handle shaft. C) Right view on an antiphase movement with markers fixed on the upper limb and handle extremities.

2.2 Protocol

The test consisted of the acquisition of kinematic and dynamic parameters during kranking performed by a young healthy male subject. The study was approved by the Local Institutional Review Board and all procedures were conformed to the Helsinki Declaration. Before the experiment, video cameras were calibrated. A board with a grid of points was placed in the field of vision of each camera according to the plane of motion of the crank handle and the human arm. Since the distance between the points in the grid was known, the software created a correspondence between each pixel in the recorded movie and a specific bi-dimensional position. Once the two video cameras were set, the synchronization between the video recording and the signals coming from the strain gauge sensors was performed through an external triggering device.

Subsequently, the cadence, torque, and motion pattern were varied to define many kranking tests enabling qualitative considerations on the effects of these parameters on the kranking activity. In detail, low and high cadences were respectively self-selected by the subject with the goal of investigating the performances at different speeds of cycling. Then, two qualitative levels (low and high) of resistant torque on the flywheel were imposed on the Krankcycle brake. Moreover, the hand-cycling style was also explored activating the two crank handles in phase or antiphase. As Table 1 shows, the most significant tests were selected and analyzed. In particular, the test condition characterized by low self-selected cadence, high braking torque, and in phase cycling pattern was assumed as the reference for the comparison of the other conditions. Once the specific experimental setting was defined, each test was repeated three times for 10 s. Data acquisition was performed in steady-state condition (after 60 s from the start) through dedicated hardware and software devices.

Table 1. Kranking characteristics of the selected tests.

	Test 1 (ref)	**Test 2**	**Test 3**	**Test 4**
Cadence (Hz)	Low	High	Low	Low
Torque (Nm)	High	High	Low	High
Pattern	In phase	In phase	In phase	Antiphase

2.3 Data analysis

Once the tests were performed, all the collected data was properly handled to extract relevant kinematic and dynamic information (Fig. 2). Exploiting the optoelectronic system, the trajectories of body markers and grip extremities (H_1 and H_2) were known. The positions of shoulders (S), elbows (E), and wrists (W) were defined in the cameras global frame. Furthermore, the centres of rotation of the crank handles (C) and the centres of the grippers (H) were identified in the cameras global frame. Then, H were related to C. Since the point of application of the force action was not directly visible in the movie frames, it was individuated geometrically. The adopted methodology consisted of measuring the position of the pin along the segment connecting the grip extremities. Since the grip was a rigid body, the relative position between its extremities and the connection point with the pin was invariable. Fig. 2 shows the reference frames (rf) taken into account in the analysis. A fixed rf 0 ($x_{0i}y_{0i}$) was placed corresponding with the rotation axis of the crank handle on the ith side, where “i” stands for the left or right side. The rf C ($x_{Ci}y_{Ci}$) was fixed to the crank and its orientation with respect to the rf 0 depends on the rotation angle θ_{Ci} of the crank itself. Then, the rf H ($x_{Hi}y_{Hi}$) was defined as linked to the handle grip. Thus, the ith force expressed in the rf H was referred to the rf 0, as described in Eq. 1:

$$F_0 = \boldsymbol{A}_{\mathrm{C}}^{0} \cdot \boldsymbol{A}_{\mathrm{H}}^{\mathrm{C}} \cdot F_{\mathrm{H}} \tag{1}$$

where F is the force action referred to the fixed rf (F_0) and the handle rf (F_{H}); $\boldsymbol{A}_{\mathrm{C}}^{0}$ is the transformation matrix defining C with respect to 0; $\boldsymbol{A}_{\mathrm{H}}^{\mathrm{C}}$ is the transformation matrix defining H with respect to C. In the following, to lighten the notation, all the vectors are expressed in the fixed reference frame, hence omitting the subscript. The torque transmitted to the device on each side was estimated as described in Eq. 2:

$$T_{\mathrm{i}} = b_{\mathrm{i}} \times F_{\mathrm{i}} \tag{2}$$

where b_i is the vector along with the crank. Accordingly, the total torque (Nm) applied by the subject was obtained as the sum of the two contributes on the right and left sides. Moreover, cadence (Hz) and phase error (deg) were calculated for each test. Subsequently, right and left performance parameters were computed as the ratio between the effective force (F_{Ef}), i.e. the force component that contributes to the forward motion of the crank, and the total force (F). Finally, the ratio between left and right effectiveness was estimated. For each test, the results of the three attempts were averaged to compare different activity conditions in terms of kinematics, forces, and effectiveness.

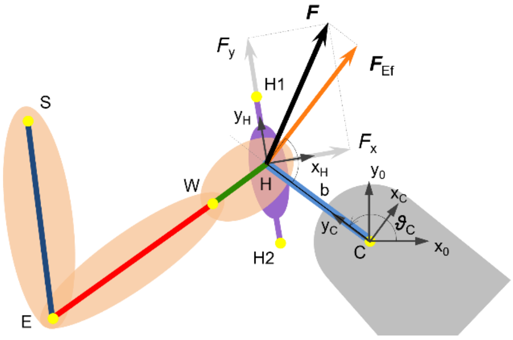

Fig. 2. Schematic description of reference frames adopted during the analysis.

3 Results and discussions

The following results refer to the performance parameters evaluated varying the testing conditions (cadence, torque, and motion pattern) with the aim of analyzing possible differences in terms of symmetry, correctness of motor activity, and proprioception.

Fig. 3 illustrates mean values of right and left effectiveness defined for all testing conditions as the ratio between the effective force F_{Ef} and the total force F. For each test, values of all repetitions were averaged and expressed over a complete rotation. According to Fig. 3, the effectiveness is not homogeneous during a single period. In the tests with the in phase pattern (Fig. 3.1, 3.2, 3.3), the effectiveness improves when the movement occurs in both the areas proximal (PR) and distal (DS) with respect to the human trunk. On the contrary, a slight worsening of effectiveness can be observed in correspondence of the superior (UP) and inferior (DW) regions. Since the participant was right-handed, Fig. 3.4 depicts a lower left effectiveness in the antiphase pattern.

Table 2 shows mean and standard deviation values of significant parameters estimated for all repetitions of the four reported conditions. The right (R) effectiveness was adequate (≥ 0.92) independently of the testing condition. However, the reduction of the braking torque (test 3) caused a slight decrease in effectiveness (-3%). Considering the left (L) weak arm effectiveness, a significant difference between in phase and antiphase gestures can be highlighted. Indeed, for the in phase conditions, both the rise of the cadence (test 2) and the reduction of the torque (test 3) produced an increase of effectiveness (+4% and +5%, respectively). On the contrary, as stated before, the antiphase condition (test 4) caused a remarkable worsening of effectiveness (-9%).

Observing the L/R effectiveness ratios, it is evident that both the rise of the cadence (test 2) and the reduction of the torque (test 3) improved the symmetry of effectiveness (+5% and +9%, respectively). On the contrary, the antiphase condition (test 4) led to a lower effectiveness ratio with respect to the reference test (-7%). Moreover, the phase error of in phase gestures is negligible (≤ 2.11 deg), whereas in antiphase conditions it is notable (12.32 deg). This confirms that, during the antiphase test, it is more difficult to maintain a constant phase delay of 180 deg between the two handles.

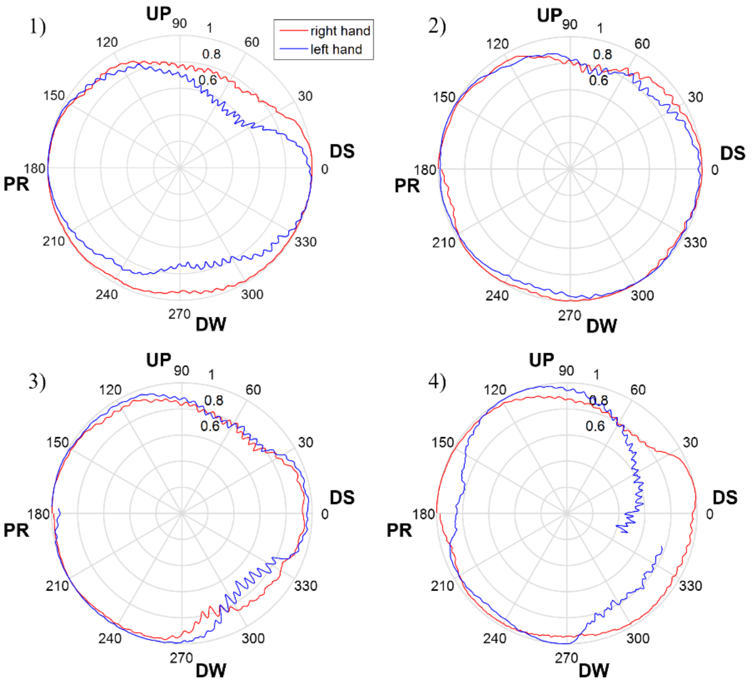

Fig. 3. Mean values of right and left effectiveness estimated as functions of the kranking angle. 1) Reference; 2) Cadence increase; 3) Torque reduction; 4) Antiphase handcycling pattern.

4 Conclusions

This pilot study aimed at validating the presented setup to quantitatively evaluate the force effectiveness and symmetry during different kranking conditions. Overall, results suggest that the current setup is suitable for highlighting deficits in terms of force effectiveness and gesture symmetry during the arm-cranking gesture. Hence, the proposed tool might be adopted to evaluate the performance through the monitoring of the effectiveness parameters. This aspect represents an improvement in different contexts such as athletic training, physical therapy, active ageing, and inclusive fitness.

The present work focused mainly on the evaluation of the force effectiveness and symmetry during the kranking activity. To provide better performance and effectiveness of training, the proposed setup has been equipped with real-time biofeedbacks of the cranking rate and left and right effectiveness and symmetry. Even additional sensors such as wearable inertial sensors and EMG sensors might be added for the extraction of other kinematic and muscular features.

Table 2. Mean and standard deviation (std) values of significant parameters.

	Test 1 (reference) **Mean (std)**	**Test 2** **Mean (std)**	**Test 3** **Mean (std)**	**Test 4** **Mean (std)**
Cadence (Hz)	0.63 (0.03)	1.31 (0.06)	0.72 (0.04)	0.63 (0.04)
Torque (Nm)	12.82 (3.59)	15.78 (3.98)	6.22 (1.71)	13.04 (1.72)
Phase error (deg)	-0.28 (1.52)	2.11 (1.80)	2.09 (1.55)	12.32 (1.86)
R-effectiveness	0.95 (0.07)	0.95 (0.06)	0.92 (0.07)	0.94 (0.07)
L-effectiveness	0.87 (0.12)	0.91 (0.08)	0.92 (0.08)	0.78 (0.19)
L/R eff. ratio	0.91 (0.09)	0.96 (0.06)	1.00 (0.05)	0.84 (0.23)

Acknowledgement

Authors thank JHT ITALIA s.p.a. – MATRIX for providing the Krankcycle® machine.

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