Jerk Decomposition during Bimanual Independent Arm Cranking

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***Abstract*— The relationship between the smoothness of the upper limb endpoint movement and multijoint angular motion is a function of the individual joint angular velocities, accelerations, and jerks as well as the instantaneous arm configuration and its rate of change during movement execution. We compared the contribution of jerk components to the total endpoint jerk in able bodied participants who performed arm cranking movements on an arm cranking device where the two arms could crank independently. The results of this investigation suggest that the most dominant components of the end effector jerk are related to both the angular jerks and to the change of arm configuration pose. This jerk partitioning is much stronger as it was found previously for both reaching arm movements and single hand cranking. This shows the task specificity of the decomposition of endpoint jerk and the effect that bi-manual tasks can have on the smoothness of movements. The proposed decomposition may give useful information in why certain bi-manual rehabilitation processes are more useful than others.**

I. INTRODUCTION

Arm cranking is a motor task, which is quite commonly applied in rehabilitation protocols. One of the major advantages of arm cranking is the possibility for the individual who is highly impaired to increase the heart rate similarly to brisk walking, for non-ambulatory individuals. The exercise is aerobic when this cyclic movement is performed continuously for sufficient time involving muscles from arms, shoulders and upper torso. There are studies about the effect of arm cycling on interlimb reflex modulation [1-3]. Application of conventional arm cycle ergometers is common in rehabilitation centers. Special arm cycle-ergometers are also developed [4-6]. Although, arm cranking has not been studied extensively, from the motor control point of view. Arm cranking can be performed by individuals with low dexterity, who might be highly impaired. It is thought that arm cranking can be performed by people with hemiparetic limbs because the unaffected side can compensate for the lack of mobility of the affected side. If compensation of the dominant arm is true, this behavior should be evident also on individuals that are not impaired as a discrepancy between the dominant and non-dominant arm. Thus, we elaborated the present experiment to identify if any discrepancy could be observed in the endpoint jerk components during an arm cranking exercise where the two cranks, rotated by the dominant and non-dominant arms are not physically connected to each other. The participants could perform the bimanual cranking by moving the arms counter-phase or in-phase. Previous studies [7-9] proposed a decomposition of the endpoint jerk that is function of the joints kinematic. We demonstrated that the relationship between such components is a good predictor of impairments when utilized in reaching movements [7]. De Lucerna and colleagues [10] have shown that bimanual jerk can be a useful tool to assess impairment. It was shown that bimanual jerk asymmetry, encodes information related to upper limb recovery. In our present study we compare the jerk decomposition observed in the left and right arm.

II. METHODS

A. *Participants*

A cohort of 12 right handed, able bodied individuals (6 woman, 6 man, 26.92+/-6.4 years) were involved in this study at the National Institute for Medical Rehabilitation, Budapest, Hungary. The Ethical Committee of the Institute approved the procedures. Participants gave written informed consent to participate in the study.

B. *Experimental Setup*

Arm cranking movements were performed on a special, custom-designed device which has unconnected handles. Each participant was seated on a chair in front of the device. The distance between the chair and the device was adjusted to the length of the participant's arm so that, when the handle of the device was at the most distant position with respect to the participant, the external angle of the elbow was 10-15 degrees. Cycling cadence was 60 revolutions per minute. A metronome guided the participant to keep this cadence. Cycling was performed bimanually in 2 conditions: with hands cracking in counter-phase (180 deg) and in phase (0 deg). The radius of the circle in which the hand moved was 10 cm. The participant cycled for 30 seconds. Ultrasound emitting markers of a movement recording and analyzer system (ZEBRIS CMS HS, Isny Germany) were placed on the participant's arm, on the crank of the device and one reference marker on the chair (Fig. 1). The coordinates of each marker's positions were recorded with 3 ultrasound sensitive microphones with a sampling frequency of 100Hz.

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C. Data Analysis

The inter-segmental angles in the shoulder, elbow and wrist (Figure 1.) were computed from marker positions using simple trigonometric equations.

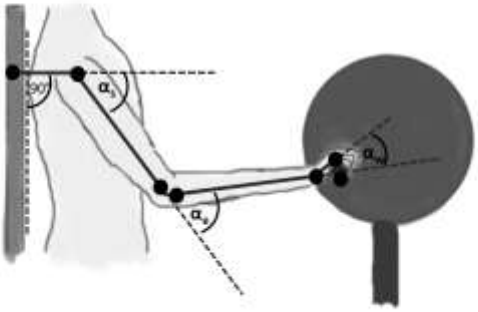


Figure 1. Markers (black dots) are placed to the participant's arm, on the crank of the ergometer and a reference marker on the chair on which the participant was seated. Joint angles in the shoulder, elbow and wrist were computed as the angle between the lines representing neighboring body segments.

We used a Savitzky-Golay averaging filter included in the Signal Processing MATLAB Toolbox to filter the time courses of joint angles and each of their derivatives with respect to time, up to the third order. We created a specific program that calculates the cutoff frequency of the filter in order to make sure we are focusing on the proper frequency of the signal and do not include unwanted noise that could arise from the numerical derivation process. We constructed a white noise random signal with the same duration and sampling frequency of our original signal. To identify the cutoff frequency we compared the Welch Power Spectrum of the random signal before and after filtering and identified the first frequency in which the change in the spectrum magnitude was -3 dB. Reliable results are obtained using a length of the window for the Savitzky-Golay filter of about 101 points (i.e. a full rotation of the crank) with a 7th order polynomial fitting the signal within the aforementioned window. This arrangement provides a cutoff frequency of about 2 Hz.

Arm configuration was defined by the inter-segmental angles of the shoulder, elbow and wrist joint (α_s, α_e, α_w) thus resulting in a 3-Dimensional joint space representation. Arm cranking is often represented as a planar movement in the sagittal plane, where the crank angular velocity ϕ'(t) is defined as a vector orthogonal to such a plane. We recognized that the movement is not completely planar since there exist a slight ab-adduction angle at the shoulder α_a of each arm. The direction of the vector of angular velocity ${\alpha_a}'$(t) passes through the instantaneous center of rotation of the shoulder and the point of contact of the hand with the crank. On the other hand, as described in several publications illustrating the Uncontrolled Manifold [5], the variance of this degree of freedom does not influence the main task since ${\alpha_a}'$(t) and $\phi\,'$(t) are always orthogonal. Conversely, any movement related to the elevation of the shoulder $\alpha_s(t)$, flexion-extension of the elbow $\alpha_e(t)$ or wrist $\alpha_w(t)$ if done independently will produced a movement of the crank $\phi(t)$. Thus, these three angles are considered the degrees of freedom that must be part of control manifold $\boldsymbol{\alpha}$ to move the crank. We define the osculating plane $\boldsymbol{\Omega}(t)$ as the plane that contains the vector ${\alpha_a}'$(t), and that is orthogonal to the instantaneous angular velocity vectors of the elbow joint.

D. Jerk decomposition

Movements of the 3-joint (shoulder, elbow, wrist) kinematic chain were investigated. The velocity of the endpoint (marker at the hand) was computed from the time derivatives of the joint angles using the Jacobian **J.**

$$\boldsymbol{p}'(t) = \boldsymbol{J}(t)\,\boldsymbol{\alpha}'(t) \tag{1}$$

The apex (′) represents the first derivative with respect to time of the endpoint position $\boldsymbol{p}(t)$ = [p_x(t), p_y(t)] and joint angular displacement **α(t)**=[α_s, α_e, α_w] where the subscript "s" refers to the shoulder joint, "e" to elbow and "w" to wrist joint, respectively. $\boldsymbol{J}$(t) is the Jacobian matrix of the subject's arm:

$$\boldsymbol{J}(t) = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \end{bmatrix}$$

The elements of the Jacobians are:

$$\boldsymbol{J_{11}} = -l_1 \sin\alpha_s - l_2 \sin(\alpha_s + \alpha_e) - l_3 \sin(\alpha_s + \alpha_e + \alpha_w)$$

$$\boldsymbol{J_{12}} = -l_2 \sin(\alpha_s + \alpha_e) - l_3 \sin(\alpha_s + \alpha_e + \alpha_w)$$

$$\boldsymbol{J_{13}} = -l_3 \sin(\alpha_s + \alpha_e + \alpha_w)$$

$$\boldsymbol{J_{21}} = l_1 \cos\alpha_s + l_2 \cos(\alpha_s + \alpha_e) + l_3 \cos(\alpha_s + \alpha_e + \alpha_w)$$

$$\boldsymbol{J_{22}} = l_2 \cos(\alpha_s + \alpha_e) + l_3 \cos(\alpha_s + \alpha_e + \alpha_w)$$

$$\boldsymbol{J_{23}} = l_3 \cos(\alpha_s + \alpha_e + \alpha_w)$$

where the time dependency of the joint displacement has been omitted for convenience. The subscripts 1, 2, 3 refer to the upper arm, forearm, and hand segments, respectively.

A double time-differentiation of (1) provides the endpoint jerk as the sum of three components:

$$\boldsymbol{p'''(t) = J''(t)\alpha'(t) + 2J'(t)\alpha''(t) + J(t)\alpha'''(t)} \tag{2}$$

Let $\mathbf{G_1}(\boldsymbol{t}) = \boldsymbol{J''(t)\alpha'(t)}$;
$\mathbf{G_2}(\boldsymbol{t}) = \boldsymbol{J'(t)\alpha''(t)}$;
$\mathbf{G_3}(\boldsymbol{t}) = \boldsymbol{J(t)\alpha'''(t)}$;

After taking the square of both sides of (2) and integrating over time we get:

$$\int_{t1}^{t2} \boldsymbol{p}'''(t)^2 dt = \int_{t1}^{t2} \mathbf{G_1}(\mathrm{t})^2 dt + \int_{t1}^{t2} \mathbf{G_2}(\mathrm{t})^2\, dt + \int_{t1}^{t2} \mathbf{G_3}(\mathrm{t})^2\, dt + \int_{t1}^{t2} 2\,(<\boldsymbol{G_1}(t), \boldsymbol{G_2}(t)> + <\boldsymbol{G_1}(t), \boldsymbol{G_3}(t)> + <\boldsymbol{G_2}(t), \boldsymbol{G_3}(t)>)dt \tag{3}$$

where < , > is vector product, $\boldsymbol{G_i}(t)^2 = <\boldsymbol{G_i}(t), \boldsymbol{G_i}(t)>$ for *i*=1,2,3, t1 is the start of the second and t2 is the start of last cycle.

This way, the integral of the square of the total endpoint jerk is partitioned into four terms. We refer to the fourth term as the integral of the “mixed components” because it depends on $\boldsymbol{G_1}, \boldsymbol{G_2}$ and $\boldsymbol{G_3}$, while the first 3 terms depend only on one of the jerk components.

The three components ($\boldsymbol{G_1}, \boldsymbol{G_2}$ and $\boldsymbol{G_3}$) are vectors in the Cartesian space. If these vectors were to be pairwise orthogonal the “mixed” integral term would vanish. If the pairwise angles between two components are less than 90 degrees but bigger than 0, than the “mixed” integral term is positive and it increases as non-mixed components get larger. The magnitude and sign of this mixed term may reflect differences in central control of various motor tasks [4].

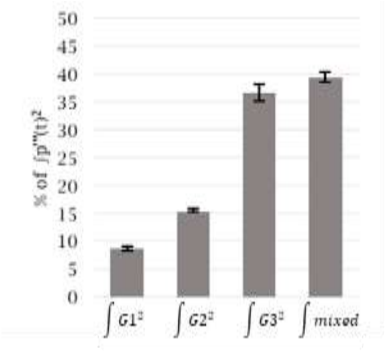
E Statistics

We calculated a multiple ways mixed factor analysis of variance (ANOVA). In the analysis we considered 4 factors such as hand=[‘left’,’right’], component=[‘$\int \mathbf{G}_3{}^2$’,’∫ mixed’], condition=[‘in_phase’,’ out_phase’’], and the subject which should be considered as a random factor and therefore makes this a mixed model. The variability of the jerk components depends upon the Jacobian (and their derivatives with respect to time) of each subject (see eq. 2). Using the subject as a (random) factor allows taking into account the inter-subject variability due to the difference in size between subjects. Furthermore, we included in the model a pairwise interaction between the factors. Mixed factor two way ANOVAs were performed both on the population of $\int_{t1}^{t2} \mathbf{G_3}(\mathrm{t})^2$ and ∫ mixed where we considered “hand” and “condition” as fixed factors and subject as a random factor.

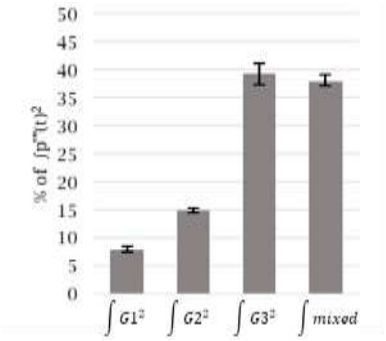
III. RESULTS

Each term of the right side of (3) was avearged across participants. Figure 2 represents the average contributions of each four integrals of the right side of equation (3) to the total endpoint jerk, that is the left side of the equation. Note that the component directly dependent on the joint angular-jerk that for brevity we will refer to as $\int \boldsymbol{G_3}^2$, and the “mixed term” (∫ mixed) which depends on the relationship between the angular velocities, accelerations and jerks, are equally dominant. The other two terms, $\int \boldsymbol{G_1}^2$ and $\int \boldsymbol{G_2}^2$, which are not depending on angular jerk, are much smaller.

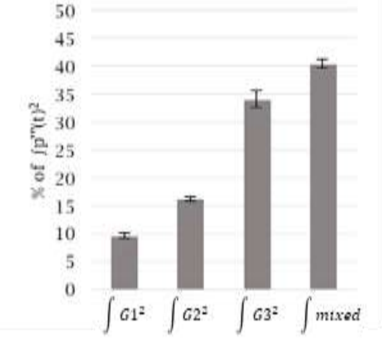
Recalling the analysis described in Sec. II.E. we found no statistical difference between $\int \boldsymbol{G_3}^2$ and ∫ mixed ($p_{component}$=0.253479 in Table I). By considering the subject as a random factor and thus eliminating the confounding factor due to the intra-subject variability we found that the two hand do behave differently for each subject, where p_{hand}=0.009603. Furthermore, there exist a statistically significant interaction between the hand factor and jerk components $p_{hand*component}$=0.001836. This indicates that while $\int \boldsymbol{G_3}^2$ is statistically not different form ∫mixed when comparing their compounded distributions coming from both hands, at least one hand produced two statistically different distribution of the same variable. This is noticeable when observing the histograms in Figure 2. It appears that the average of ∫mixed term stays pretty much unchanged independently of hand and condition. Conversely, $\int \boldsymbol{G_3}^2$ is seems different between the two hands, and we can observe that $\int \boldsymbol{G_3}^2$ is higher for the left hand.



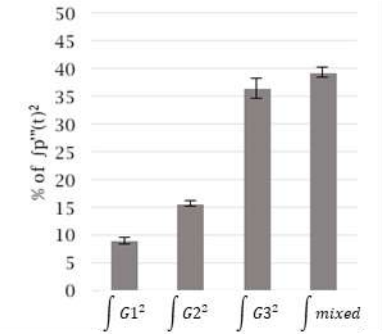
Right arm – out of phase



Left arm – out of phase



Right arm – in phase



Left arm – in phase

Figure 2. Mean (across participants) contribution of the structural components to the the total squared endpoint jerk (as percentages of the total squared endpoint jerk). Diagrams show results for in phase and out of phase cranking for the right and left arm. Vertical lines above the bars denote standard errors

TABLE I. MIXED FACTOR ANOVA BETWEEN ∫G3AND ∫MIXED

'Source'	**Sum Sq.**	**d.f.**	**Mean Sq.**	**'F**	**'Prob>F'**
'hand'	10.092	1	10.09286	9.787	**0.009603**
'subject'*	180.92	11	16.44731	0.153	0.997324
'component'	175.0	1	175.052	1.452	0.253479
'condition'	16.422	1	16.42282	11.17	**0.00656**
'hand*subject'*	11.34	11	1.031171	0.129	0.999572
'hand*component'	87.45	1	87.45301	10.96	**0.001836**
'hand*condition'	0.0017	1	0.001771	0.000	0.988176
'subject*component'*	1326.0	11	120.5526	15.11	1.08E-11
'subject*condition'*	16.1	11	1.469668	0.184	0.997776
'component*condition'	88.1	1	88.17633	11.05	**0.001765**
'Error'	358.8	45	7.97506	[]	[]
'Total'	2270.5	95	[]	[]	[]

**indicates random factor*

TABLE II. MIXED FACTOR ANOVA FOR SINGLE COMPONENTS

G3 only					
Source	**Sum Sq.**	**d.f.**	**Mean Sq.**	**F**	**Prob>F**
‘hand’	78.48	1	78.48	7.867	**0.01712**
‘subject’*	1206.5	11	109.6	5.226	0.00084
‘condition’	90.35	1	90.35	7.281	**0.02077**
‘hand*subject’*	109.7	11	9.975	7.144	0.00144
‘hand*condition’	0.141	1	0.141	0.101	0.75635
‘subject*condition’*	136.5	11	12.40	8.88	0.00054
‘Error’	15.35	11	1.396	[]	[]
‘Total’	1637.1	47	[]	[]	[]
G mixed only					
Source	**Sum Sq.**	**d.f.**	**Mean Sq.**	**F**	**Prob>F**
‘hand’	19.06	1	19.06	3.283	0.09734
‘subject’*	300.4	11	27.31	2.853	0.02355
‘condition’	14.24	1	14.24	3.069	0.10759
‘hand*subject’*	63.86	11	5.805	6.631	0.00199
‘hand*condition’	0.100	1	0.100	0.114	0.74163
‘subject*condition’*	51.05	11	4.641	5.301	0.00507
‘Error’	9.630	11	0.875	[]	[]
‘Total’	458.3	47	[]	[]	[]

**indicates random factor*

A statistical analysis done for each independent condition as described in Sec II.E shows that the term $\int$ mixed is indeed statistically the same independently of the handiness and condition (Table II), whereas $\int \boldsymbol{G_3}^2$ depends both on handiness and condition. In both cases the mixed term $p_{hand*component} > 0.75$. This indicates that the two hands seems to produce the same outcome for ∫mixed independently of the condition, the difference in $\int \boldsymbol{G_3}^2$ due to handiness and condition compensate themselves acting in different direction. Indeed $\int \boldsymbol{G_3}^2$ is higher for the left hand when compared to the right hand but lower when in the in-phase condition as supposed to the out-of-phase (Figure 2). Examples of raw data for the components of (3) are presented in Figure 3.

DISCUSSION

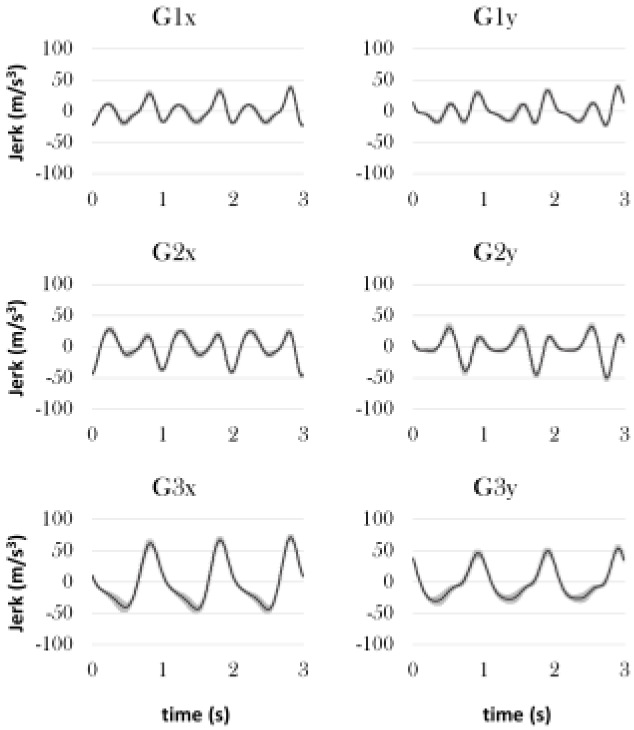
In a point to point reaching movement the dominant component influencing the behavior of the endpoint jerk was directly related to the angular jerk [7]. When analyzing arm cranking movement we found that the angular jerk component is not sufficient to mainly represent the endpoint jerk. Especially, the integral of the total squared endpoint jerk is very much affected by the integral of the “mixed term” [9]. The $\int \boldsymbol{G_3}^2$ component contributes now to less than 40% of the magnitude of the total jerk in contrast to the over 90% that was previously found for reaching movements [7], and 60% in unilateral cycling [9]. In unilateral cycling the $\int G_3^2$ and ∫mixed are statistically different and $\int \boldsymbol{G_3}^2$ is usually higher than ∫mixed (of 20% or more).

The mixed term is a figure of merit for the co-ordination of multi-join movements. The sign and magnitude of the integral of the mixed term well characterize differences in motor execution. Earlier, it was shown that this integral was negative when stroke survivors with severe impairment performed reaching movements while for unimpaired participants the sign was positive [7]. The previous study about reaching arm movements and our present study shows that the magnitude of this integral depends very much on the motor task.

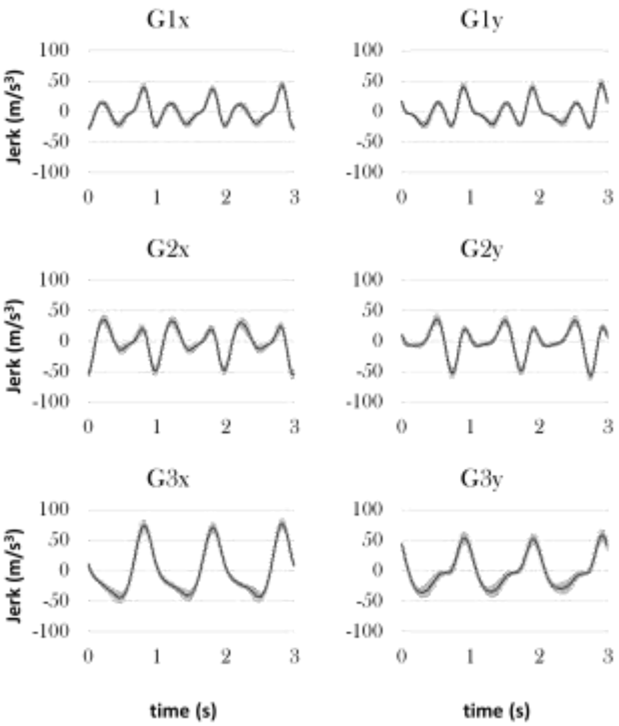
Given that in the present study ∫mixed is not statistically different between hands and conditions in this specific task where the two hands crank together but are not physically connected through the crank shaft, supports the idea of a separate control system controlling the co-ordination of the two arms. It is important to note that while reaching movements can be characterized using some form of position control, arm cranking requires the control of the cadence and thus indirectly the control of the hand velocity. This could be a less onerous task that could be controlled via an autonomous oscillator model [12], where the interaction impedance between the two arms can be controlled. We can speculate that this control does not substitute the independent controls of each limb but acts in parallel to them. The analyses of the $\int \boldsymbol{G_3}^2$ component still show statistically significant differences between the jerk of the right and left arm, indicating that handiness is still present albeit in a much attenuated fashion.

Bimanual co-ordination is often studied in conjunction with visual feedback. Studies on children affected by cerebral palsy [13] highlighted that mirror visual feedback (e.g. a mirror box) has a positive effect in bimanual tasks. However, the result was not exclusively dependent on the perception of the two limbs moving symmetrically while moving only one and seeing the reflection of it.

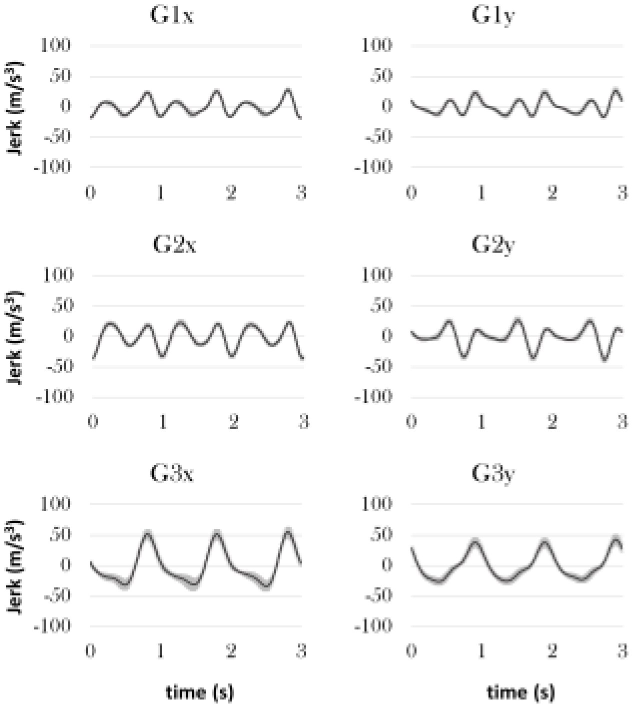
Right arm – out-of-phase



Right arm – in-phase



Left arm – out-of-phase



Left arm – in-phase

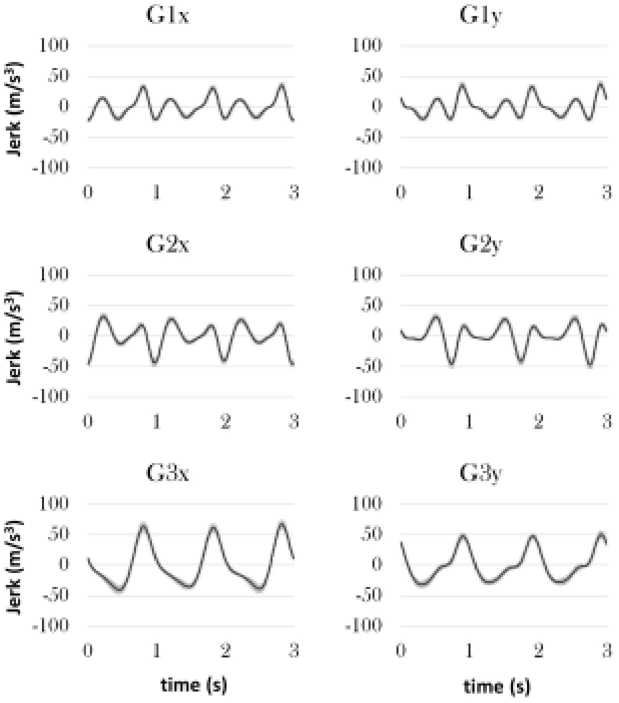


Figure 3. Cartesian components of the endpoint jerk during 3 selected cycles of arm cranking, averaged across participants. Mean values and standard errors are represented. Note the different magnitudes for each component. The 3rd component ($G3(t)$) dominates the total jerk. The first and second components are small. Right arm (upper diagrams), left arm (lower diagrams).

In order to induce a decrease in abnormal muscular activity in the impaired limb, mirror visual feedback from the unimpaired limb is required. It is therefore necessary to move both limbs to obtain synchronization, since only visual feedback (i.e. following the movement of a projected limb) does not engage proper co-ordination. In light of these previous finding, our results is consistent with the notion of an independent control for bimanual task that does not depend on the lateralization. We can speculate that $\int$mixed is a figure of merit of such co-ordination control, while $\int \boldsymbol{G_3}^2$ is more representative of the outcome of lateralization.

The studied components of the end effector jerk depend on the arm configuration and on the change of am configuration in a complex manner. Further research is required to deepen the understanding of the role of such jerk components. The information presented in this paper can provide a new prospective on the creation of rehabilitation therapies and robotic devices because it encourages taping into resources that are seldom utilized in the rehabilitation practice. While training often occurs unilaterally and on the impaired side, the use of bi-manual training could allow using the co-ordination between the two limbs to improve the smoothness of the lateralization component and therefore increase the smoothness for the impaired limb.

It has already been demonstrated that there were no significant differences in variances of arm configurations observed in the dominant and non-dominant arm using such ergometers for arm cycling where the subject acts upon a crank that physically connects the two hands [14]. In the present study an unusual, novel arm cranking task was studied using an unusual device in which the two cranks, rotated by the dominant and non-dominant arms, were not connected.

In this work we propose that advancing the knowledge of limb co-ordination in unimpaired neuro-behavioral systems and understanding of special bimanual motor tasks can be applied specifying novel medical rehabilitation protocols. As a consequence clinicians could better chose a therapy to maximize and also to evaluate functionality [15].

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