Subject specific muscle synergies and mechanical output during cycling with arms or legs

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Background. Upper (UL) and lower limb (LL) cycling is extensively used for several applications, especially for rehabilitation for which neuromuscular interactions between UL and LL have been shown. Nevertheless, the knowledge on the muscular coordination modality for UL is poorly investigated and it is still not known whether those mechanisms are similar or different to those of LL. The aim of this study was thus to put in evidence common coordination mechanism between UL and LL during cycling by investigating the mechanical output and the underlying muscle coordination using synergy analysis.

Methods. Twenty-five revolutions were analyzed for six non-experts' participants during sub-maximal cycling with UL or LL. Crank torque and muscle activity of eleven muscles UL or LL were recorded. Muscle synergies were extracted using nonnegative matrix factorization (NNMF) and group- and subject-specific analysis were conducted.

Results. Four synergies were extracted for both UL and LL. UL muscle coordination was organized around several mechanical functions (pushing, downing, and pulling) with a proportion of propulsive torque almost 80% of the total revolution while LL muscle coordination was organized around a main function (pushing) during the first half of the cycling revolution. LL muscle coordination was robust between participants while UL presented higher interindividual variability.

Discussion. We showed that a same principle of muscle coordination exists for UL during cycling but with more complex mechanical implications. This study also brings further results suggesting each individual has unique muscle signature.

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18 Abstract
19 **Background.** Upper (UL) and lower limb (LL) cycling is extensively used for several
20 applications, especially for rehabilitation for which neuromuscular interactions between UL and
21 LL have been shown. Nevertheless, the knowledge on the muscular coordination modality for
22 UL is poorly investigated and it is still not known whether those mechanisms are similar or
23 different to those of LL. The aim of this study was thus to put in evidence common coordination
24 mechanism between UL and LL during cycling by investigating the mechanical output and the
25 underlying muscle coordination using synergy analysis.
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27 maximal cycling with UL or LL. Crank torque and muscle activity of eleven muscles UL or LL
28 were recorded. Muscle synergies were extracted using nonnegative matrix factorization (NNMF)
29 and group- and subject-specific analysis were conducted.
30 **Results.** Four synergies were extracted for both UL and LL. UL muscle coordination was
31 organized around several mechanical functions (pushing, downing, and pulling) with a
32 proportion of propulsive torque almost 80% of the total revolution while LL muscle coordination
33 was organized around a main function (pushing) during the first half of the cycling revolution. LL
34 muscle coordination was robust between participants while UL presented higher interindividual
35 variability.
36 **Discussion.** We showed that a same principle of muscle coordination exists for UL during
37 cycling but with more complex mechanical implications. This study also brings further results
38 suggesting each individual has unique muscle signature.

39

40

Introduction

Cycling with the upper (UL) or lower limbs (LL) both consists in producing torque in a circular movement with fixed cranks length around a fixed rotation axis. Cycling is extensively used for improving health, training, physiological evaluation, or rehabilitation with LL (Faria, Parker & Faria, 2005; Fujiwara et al., 2005; Oja et al., 2011; Sitko et al., 2020) and to a lesser extent with UL (Hübner-Wozniak et al., 2004; Elmer, Danvind & Holmberg, 2013; Zinner et al., 2016; Zhou et al., 2017). An increasing number of studies highlight the interest of UL cycling also for LL rehabilitation: for example, Kaupp et al. (2018) showed functional and neurological improvements of walking capacities after a rehabilitation protocol involving UL cycling. Moreover, modulations of cutaneous reflex and muscle activities of the LL was also shown after UL cycling training (Zehr & Chua, 2000; Zehr, 2005; Barzi & Zehr, 2008; Mezzarane, Nakajima & Zehr, 2014). These examples suggest similarities in movement execution and interactions in the production of movement with the UL and LL that can be observed at muscle activity level. This latter point is particularly interesting from a clinical point of view since intervention at the UL could benefit the LL functional aspects.

To deeply understand the movement of cycling, it remains crucial to understand the underlying muscle coordination. Muscle coordination leads to the question of understanding how the large number of available muscles are coordinated to execute a movement (Bernstein, 1967; Latash, 2012). The muscle synergy analysis is frequently used to answer this question (d'Avella, Saltiel & Bizzi, 2003; Turpin, Uriac & Dalleau, 2021). During LL cycling, it has been shown that muscle synergies are shared across participant despite interindividual variability of EMG pattern (Hug et al., 2010; De Marchis et al., 2013). Further studies showed that this movement is executed, from a kinematic and kinetics point of view, in the same way by any healthy person, expert or not (Mornieux et al., 2008). This analysis assumes that the Central Nervous System (CNS) simplifies the abundance of muscles by using smaller numbers of functional elements activated in time. Muscles synergies thus allow a global understanding of the muscle coordination in comparison to the production of a mechanical output. The existence of muscle synergies on the LL during cycling has been widely demonstrated even when manipulating various mechanical constraints such as posture or output torque intensity (Hug et al., 2011).

In comparison to LL cycling, UL cycling muscular coordination remains poorly understood despite the interests for training and clinical applications. A single recent study aimed to extract muscle synergies during UL cycling (Botzheim et al., 2021). Using a set of four muscles for each arm, these authors showed that bimanual muscle coordination can be described by muscle synergies. However, no simultaneous analysis of the mechanical output was performed and only a few numbers of representative muscles were used to fully understand the functional synergies during UL cycling. More generally, it remains unknown whether the UL synergies are similarly organized than in LL with respect to the mechanical output. Unfortunately, this lack of knowledge limits the potential for these exercises to be objectively used for training and clinical applications.

Complementary, several studies highlight the necessity to take into account individual differences (Bartlett, Wheat & Robins, 2007) and a recent work of Hug et al. (Hug et al., 2019)

85 put in evidence that individuals have unique muscle signatures. Each individual muscle
86 signature could result from numerous individual factors such as development, experiences, or
87 diseases discrepancies. Contrary to LL, UL musculoskeletal system offers the possibility to pull
88 or push equally, allowing several possible strategies in movement execution. Individual
89 differences in synergies can thus be differently managed in the UL compared to LL.
90
91 The first objective of this study was thus to fill the knowledge gap by investigating the
92 simultaneous temporal evolutions of the mechanical output and of the EMG and muscle
93 synergies of the Upper Limb in comparison to the Lower Limb during cycling. To individualize
94 our analysis, our second objective was to compare interindividual variability between UL and LL
95 at kinematics, kinetics, and muscle coordination levels.
96

Materials & Methods

Participants

99 Six young healthy adults (age: 27.2 ± 2.9 years; weight: 69 ± 7.5 kg; height: 174,2 ± 5.1 cm)
100 volunteered to participate in the study and suffered of no injuries in the past 6 months. To limit
101 the effect of participants' level, expertise in either UL or LL cyclic exercise constituted an
102 exclusion criterion. Participants gave their written consent and were informed of the possible
103 risks and discomfort associated with the experiment. The experimental protocol was approved
104 by the national ethic committee (CERSTAPS, IRB00012476-2020-30-11-75) and the study was
105 conducted in accordance with the Helsinki declaration.
106

Experimental procedure

108 The experimental session consisted in two phases performed successively with the UL or the LL
109 in random order. Before each phase, participants performed a 5-minutes standardized warm up
110 with the tested limb at self-selected cadence (SSC: 85.0±10.4 vs 86.3±9.8rpm, p>0.05, for arms
111 and legs respectively). The self-selected cadence was then used and controlled for the entire
112 protocol. To estimate maximal power (MP), participants performed a single 10 seconds
113 isokinetic all-out with strong verbal encouragements. MP was computed as the mean peak
114 power during the 10 seconds. The same relative amount of power was set at 30% of MP to
115 reach a significant intensity without any excessive fatigue and to compare both limbs at the
116 same relative mechanical demands. Participants then performed a submaximal 2-minute test at
117 30% of MP at self-selected cadence (102.8±14.7 vs 171.7±34.4W, p<0.05, for arms and legs
118 respectively). The two experimental phases were separated by at least 35 min rests to limit the
119 fatigue effect and change the experimental equipment (EMG, markers etc.) from one limb to
120 another.
121

Material and data collection

123 *Ergometer.* The task was performed on a cycle ergometer (Excalibur for LL and Brachumera for
124 UL, Lode, Groningen, The Netherlands) equipped with standard cranks, flat pedals for feet and
125 standard horizontal pegs for hands. The type of pedals interface was chosen to study the most
126 ecological situation for each limb. For LL cycling, participants were asked to seat comfortably on
127 the saddle and maintain their position during the entire experimental procedure. For UL cycling,
128 participants were seated in front of the ergometer in pronated grip (figure 1). The crank axis

129   height was positioned at the glenohumeral level. Participants were preferentially seated on a
130   chair and were instructed not to grab the chair legs with their own legs. Torque and pedalling
131   frequency were recorded each 2 degrees by the Lode Ergometry Manager software.
132   Ergometers were calibrated before each evaluation.
133

Figure 1: Experimental set-up.
Left column: Example of experimental set-up for UL (top) and LL
(bottom) and schematic representation of the cycle revolution for each. The
green dot represent the SH to FH transition and the red dot the FH to SH
transition. FH: first half, SH: second half

134
135   *Kinematics.* Kinematics was recorded using 5 Qualisys cameras (Oqus 7) at 200Hz with
136   Qualisys Track Manager software (Qualisys, Sweden). Trajectories of five reflective markers
137   placed on distal extremity of the *5th metacarpal, ulnar styloid, lateral epicondyle, acromion* and
138   *iliac crest* and distal extremity of the *5th metatarsal, lateral malleolus, lateral knee epicondyle,*
139   *greater trochanter* and *iliac crest* were used to compute the 2D angular trajectories of the ankle,
140   knee, hip and wrist, elbow, shoulder joints.
141
142   *EMG.* The electromyography of 22 muscles were recorded using EMG system (Wireless
143   System, DELSYS, USA) sampled at 2000Hz with the Delsys Trigno Acquisition software. Before
144   electrode application, the skin was shaved and cleaned with an alcoholic solution to improve the
145   electrode/skin impedance. SENIAM recommendations were followed to ensure correct electrode
146   placement and avoid crosstalk between EMG signals. A functional test was carried out for each
147   muscle to ensure correct electrode placement. The following LL muscles were recorded: *Tibialis*
148   *Anterior* (TA), *Soleus* (Sol), *Gastrocnemius Medialis/Lateralis* (GM, GL), *Vastus*
149   *Medialis/Lateralis* (VM, VL), *Biceps Femoris* (BF), *Semimembranosus* (SM), *Rectus Femoris*
150   (RF), Tensor Fasciae Latae (TF) and *Gluteus Maximum* (GMAX) (Hug & Dorel, 2009; Hug et al.,
151   2010, 2011; De Marchis et al., 2013). The following UL muscles were recorded: *Extensor Carpi*
152   *Radialis Longus* (ECRL), *Flexor Carpi Radialis* (FCR)*, BrachioRadialis* (BR), *Biceps Brachii*
153   (BB), *Triceps Brachis Longus / Shortus* (TBL, TBS), *Deltoid Anterior / Posterior* (DA, DP) (Zehr
154   2000; Barzi & Zehr, 2008; Zehr et al., 2012; Chaytor 2020), *Pectoralis Major* (PM)*, Latissimus*
155   *Dorsi* (LD)*, Flexors Digitorum Superficialis* (FDS). EMG, torque, and kinematic recording were
156   synchronized via a trigger impulse.
157

Data processing
159   *Torque and kinematics.* Marker trajectories and torque data were low pass filtered (4th order,
160   zero-time lag Butterworth 6Hz). Absolute 2D angle of the LL (Hip, Knee, Ankle) and UL
161   (Shoulder, Elbow Wrist) were computed using vector coordinates of each segment in a sagittal
162   plane of the ergometer. Pedalling revolutions were extracted using the position of the distal
163   marker. For LL, 0° was defined as the higher position of the pedal and 180° as the lower
164   position. For UL, 0° was define as the nearest position of the pedal, when the crank is
165   horizontally directed towards the participant and far 180° the farthest when the crank is
166   horizontally directed to the opposite of the participant. Two phases are considered in the
167   movement, the First Half (FH) from 0° to 180° and the Second Half (SH) from 180° to 360°. The
168   FH to SH transition was thus when the limb is fully extended and the SH to FH transition when

169 the limb is grouped. To normalize torque between participants, absolute values were divided by
170 body mass.

171

172 *EMG pre-processing.* EMG data were first filtered using a bandpass 4th order Butterworth zero-
173 time lag filter (20-400Hz) then full wave rectified and low pass filtered (4th order Butterworth,
174 zero-time lag 4Hz) to obtain EMG envelops. For amplitude analysis, the EMG data were
175 normalized by the maximal value recorded during the 10 seconds all-out. A dedicated detection
176 algorithm has been used to select the 25 most representative cycles over the entire dataset
177 (Sangeux & Polak, 2015).

178

179 After revolution extraction and pre-processing, torque, kinematics, and EMG data were
180 resampled to 200 points by revolution.

181

182 *Synergy extraction.* Since the aim of our study was to quantify muscle coordination, EMG data
183 were normalized by the maximal value across the cycles before synergy extraction and
184 synchronous muscle synergy model was used to extracted synergies (1):

$$V_O(t) = V_R(t) + \varepsilon(t) \quad \text{with } V_R(t) = \Sigma_{s=1}^{K} H_s(t) W_s \qquad (1)$$

186 Where $V_O(t)$ indicates the initial EMG values of all muscles at time instant t, $V_R(t)$ is the
187 reconstructed signal resulting from the linear combination of W_s (the muscle synergy vector for
188 the s-th synergy) and $H_s(t)$ (the value of the synergy activation coefficient for the s-th synergy at
189 time instant t). *K* is the number of synergies necessary to reconstruct the initial EMG dataset,
190 and $\varepsilon(t)$ represents noise. This model is a compromise that allows the analysis of both spatial
191 (through W) and temporal (through H) structures of the motor outputs (Turpin, Uriac & Dalleau,
192 2021).

193

194 Nonnegative Matrix Factorization (NNMF) algorithm was applied to a matrix containing the
195 envelop of the 11 muscles across 25 cycles. The algorithm approximates the initial signal V_O
196 with a reconstructed matrix $V_R = WxH$ by minimizing the Frobenius norm $\|V_O - V_R\|$ where *W* is a
197 *K* x 11 matrix of the synergy vectors and *H* is a *K* x 5000 (25 cycles * 200 time points). The
198 algorithm was run for K in range from 1 to 10 and 10 times for each K synergies combinations to
199 avoid local minima and keep the best solution for further analysis.
200 The number of synergy sufficient to reconstruct the original matrix V_O was set by the calculation
201 of the Variance Accounted For (VAF) by V_R on the entire matrix (VAF$_{tot}$) and for each muscle
202 individually (VAF$_m$) with following equations:

$$VAF_{tot} = 1 - \frac{\Sigma(VO_{tot} - VR_{tot})^2}{\Sigma VO_{tot}^2} \qquad (2)$$

$$VAF_m = 1 - \frac{\Sigma(VO_m - VR_m)^2}{\Sigma VO_m^2} \qquad (3)$$

205

206 The minimum number of synergies that explain at least 90% of VAF$_{tot}$ and 75% of VAF$_m$ was
207 chosen. An example of reconstructed vs original EMG pattern was shown on figure 2. When
208 both VAF constraints are satisfied (i.e., total VAF and by muscle VAF), 4 synergies were

209 extracted for each participant to allow an analysis and a functional comparison between
210 participants.
211

Figure 2: Reconstructed vs original EMG pattern.
Example of reconstructed vs original EMG pattern for representative participant for LL muscles (left)
and UL muscles (right).

212
213

Statistical analysis

214
215 For each temporal data (Angle, Torque, EMG and Hsyn), the inter- or intra-individual variability
216 was calculated using a Pearson correlation coefficient r (r_{inter} or r_{intra}) and a Variance Ratio
217 parameter (VR_{inter} or VR_{intra}).
218 For interindividual variability, the input matrix X was composed of a mean curve across the 25
219 cycles for each participant (final size = 6x200). For intraindividual variability, the input matrix X
220 was composed of the 25 cycles for each participant, (final size = 25x200).
221 The VR was computed as follow:

222
$$VR_a = \frac{\sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij} - \overline{X}_i)^2/k(n-1)}{\sum_{i=1}^{k}\sum_{j=1}^{n}(X_{ij} - \overline{X})^2/(kn-1)} \quad \text{with } \overline{X} = \frac{1}{k}\sum_{i=1}^{k}\overline{X}_j \qquad (4)$$

223 Where a stand for inter or intra, k is the number of samples (k=200), n is the number of
224 participants/cycles (i.e., 6/25), X_{ij} is the value at the ith sample for the jth participant/cycle, $\overline{X}_i$ is
225 the mean value at the ith sample over the n participants/cycles.
226
227 The Variance Ratio parameter has been used in other studies (Burden, Trew & Baltzopoulos,
228 2003; Hug et al., 2010; De Marchis et al., 2013) as an indicator of the overall variation of the
229 data with respect to a mean profile: the higher the VR, the higher the inter or intra participants
230 variability in the dataset. The Pearson correlation coefficient r was computed for inter individual
231 variability between each pair of participants excluding autocorrelation and a mean±sd value is
232 presented (table 1-2). For intra-individual variability, r was computed between each pair of cycle
233 for each participant excluding autocorrelation and a mean±sd value across all participants is
234 presented (table 3-4). The Pearson correlation coefficient r indicates the similarity in the shape
235 profile of the data without being impacted by amplitude differences. We also used this
236 coefficient r to compute similarities across participant in muscle synergy vectors (W_s).
237
238 Because VR and r do not take account a possible time shift between two identical curves, the
239 normalized cross-correlation function was computed and allowed to extract the percentage of
240 shift (t_{max}) needed to maximize the cross-correlation function (r_{max}). r_{max} and t_{max} were only
241 computed for interindividual variability, intraindividual variability (through VR and r) being low for
242 each participant. Even though these four variables (VR, r, t_{max}, and r_{max}) are redundant, they
243 allow to nuance the interpretation of the variability according to differences in time, amplitude, or
244 patterns. Furthermore, these different data allow an easier comparison of our results with the
245 literature.
246
247 We performed correlations between the variables presenting high t_{max} (H_s, Torque) and the RPM
248 to further analyze the relationships between the Realization variables and the Performance
249 variables (see Discussion section for the definition). The time-shift of each synergy activation

250 coefficient (H_s) was computed by extracting the normalized time instants of max(H_s) and
251 Pearson r correlations were performed for all participants between each time-shift and pedaling
252 cadence.

Results

Torque

255 The figure 3 shows the averaged torque applied on the right pedal for UL (top) and LL (bottom).
256 Maximal peak torque was higher for LL than UL (0.72±0.12Nm/kg vs 0.18±0.30Nm/kg). For UL,
257 the output torque was positive during most of the cycle (85±9%) excepted at the end of SH and
258 maximal torque was produced at the beginning of SH (around 199±42°). For LL, the torque was
259 positive during FH (52±2% of the total cycle) and negative during SH. Maximal torque was
260 produced about mid-FH (87±8°).

261

Figure 3: Crank torque across the cycling revolution.
Mean±sd right crank torque of each subject for UL (top) and LL (bottom). A schematic representation of the cycling revolution. The red point illustrates the FH to SH transition, and the green point illustrates the SH to FH transition or upper transition for upper and lower limbs respectively. FH: First Half; SH: Second Half. UL: upper limbs; LL: lower limbs.

262

Joint kinematics

264 Figure 4 shows the kinematics of proximal, intermediate, and distal joints for LL (left) and UL
265 (right). Hip and knee angular displacements result from extension during FH and flexion during
266 SH. Ankle angular displacement result from plantar flexion in FH then dorsiflexion during SH.
267 Shoulder angular displacement results from antepulsion until mid of FH then retropulsion until
268 almost the end of crank revolution. Elbow angular displacement results from extension during
269 FH then flexion during SH. Wrist angular displacement results from extension during FH then
270 flexion during SH.

Figure 4: Kinematics pattern across the cycling revolution.
Mean±sd angle (degree) of proximal, intermediate, and distal articulations of LL (left) and UL (right). torque of each subject for UL (top) and LL (bottom). The red point illustrates the FH to SH transition, and the green point illustrates the SH to FH transition or upper transition for upper and lower limbs respectively. FH: First Half; SH: Second Half. UL: upper limbs; LL: lower limbs

271

Synergies description

273 *UL*. Four synergies were extracted for each participant (figure 5-UL) and explained 96±0.01% of
274 the total variance of the initial EMG dataset (VAF$_{tot}$) and 95±0.05% of each initial individual EMG
275 dataset (VAF$_m$). The **first synergy (S$_1$)** included the TBS and TBL during the transition from SH
276 to FH and the first part of FH. The **second synergy (S$_2$)** was composed by the activations of the
277 hand flexors (FDS and FCR) and LD during end of FH and the transition from FH to SH (90-
278 180°). The **third synergy (S$_3$)** involved hand flexors (FDS/FCR) and extensors (ECRL), elbow
279 flexors (BB and BR), elbow extensors (TBS) and shoulder extensor (DP) during SH (180-270°).
280 The **last synergy (S$_4$)** involved DA and PM in anticipation to the SH to FH transition (270-0°).

281

282 *LL.* Four synergies were extracted for each participant (figure 5-LL) and explained 96±0.02% of
283 VAF$_{tot}$ and 95±0.05% of VAF$_m$. The **first synergy (S$_1$)** involved hip flexors (RF, TF) and
284 extensors (GMAX, BF, SEM), knee extensors (RF, VM, VL) and SOL and was active around the

285 upper transition and the first part of FH (270-90°). The **second synergy (S₂)** involved ankle
286 plantar-flexors (SOL, GL, GM), hip extensors (BF, SEM) and occurred during at mid-FH (around
287 90°). The **third synergy (S₃)** located around the bottom transition (180°), involved ankle plantar-
288 flexors (GL) and hip flexors (TF). The **fourth synergy (S₄)** involved principally the TA and to a
289 lesser extent the RF and TF during SH (180-0°).
290

Figure 5: Muscle's synergy parameters and variability.
Muscle synergies for LL (left) and UL (right). A-Muscle's synergies vectors (W_s) for each muscle
(mean±sd). B-Mean synergy activation coefficient (H_s) for each subject. C-Boxplot of activation
coefficient peak occurrences across the cycle revolution during 25 cycles for each subject (each row). The
boxplot showed interindividual variability in the occurrence of the peaks for each activation coefficient:
the participants 1 and 2 showed synchronous synergy occurrence, the participant 3 showed an early peak
for each synergy and the participants 4, 5 and 6 showed latter peaks for each synergy. The detail of $r_{inter-Hs}$
showed high correlation between participants 1 and 2 ($r_{inter-1/2}$ =0.95) and between participants 4, 5 and 6
($r_{inter-4/5/6}$>0.94). The third participant showed weak or negative correlation with all the others.

291
292 **Interindividual variability**
293 The results concerning the interindividual variability are described in table 1 and 2.
294

Table 1: Interindividual variability for UL. Variance Ratio (VR), r-Pearson (r), maximum
value of cross-correlation function (r_{max}) and time lag (t_{max}) of Kinematics, torque, EMG
patterns, synergies vectors (W_s) and synergy activation coefficients (H_s). UL: upper limbs

295

Table 2: Interindividual variability for LL. Variance Ratio (VR), r-Pearson (r), maximum
value of cross-correlation function (r_{max}) and time lag (t_{max}) of Kinematics, torque, EMG
patterns, synergies vectors (W_s) and synergy activation coefficients (H_s). LL: lower limbs

296
297

298 *Joint kinematics.* UL showed slightly more angular kinematics variability than LL. The distal joint
299 showed more variability than the proximal and intermediate joints for both UL and LL. Negligible
300 time shifts in kinematic patterns were found for both limbs (table 1-2 - Kinematics & dynamics).
301

302 *Torque.* UL showed more interindividual variability in torque production than LL (VR$_{UL}$=0.26, r$_{UL}$ =
303 0.72±12 vs VR$_{LL}$ = 0.04, r$_{LL}$=0.97±0.01 respectively, p<0.05). A low time shift was found at the
304 maximum of the cross-correlation for both limbs (t$_{max-UL}$ = 2.37±2.46; t$_{max-LL}$ = 0.81±0.78). These
305 results indicates that interindividual variability in torque pattern mainly lies in differences in the
306 pattern that is produced and not in a time shifting of similar patterns. Nevertheless, considering
307 the amount of variability, even with a higher value for UL, a similar pattern of torque is produced
308 by participants (table 1, figure 3).
309

310 *EMG.* Compared to LL, UL EMG patterns showed high interindividual variability for all muscles
311 (VR$_{EMG-UL}$ = 0.68±0.22 > VR$_{EMG-LL}$=0.32±0.22, r$_{EMG-UL}$= 0.36±0.17 < r$_{EMG-LL}$= 0.71±0.24, p<0.05,
312 Table2-3-EMG). For LL, only GL, TA, BF, SEM and TF muscles showed high variability (VR >
313 0.37, r>0.64 ± 0.28), these muscles being mainly involved in S₃ and S₄ and not associated to the
314 production of propulsive torque. An important time shift was found at the maximum of cross-
315 correlation function for UL (t$_{max-EMG-UL}$=15,01±4% of the total cycle, table 1-EMG) compared to LL

316   ($t_{max-EMG-LL}$=7.9±9.3%, p<0.05, excepted for TA and TF, table 2-EMG). See supplementary figure
317   3 and 4 for mean±sd representation of each individual muscle pattern for UL and LL respectively.
318
319   *Synergies.* The interindividual variability observed at the EMG level is reflected in the synergy
320   activation coefficients, with greater interindividual variability for UL than LL (VR_{Hs-UL}
321   =0.59±0.13>VR_{Hs-LL}=0,26±0.18, r_{Hs-UL} = 0.38±0.07 < r_{Hs-LL} = 0.74±0.17, p<0.05). A larger time
322   shift was found for all UL synergies ($t_{max-Hs-UL}$=12.96±1.17 > $t_{max-Hs-LL}$ = 5.31±3.73%, p<0.05)
323   despite a good index of similarity at the maximum of r_{max} function ($r_{max-Hs-UL}$:= 0.87±0.05 and $r_{max-Hs-LL}$
324   = 0.93±0.06). UL and LL W_s showed similar correlation coefficients (0.74±0.02 vs 0.69±0.21
325   for UL and LL respectively) excepted for S_3 of LL (r_{S3}=0.39±0.37).
326
327   *Correlation in time shifts.* The correlations in time shifting of the synergies were all significant for
328   UL (figure supplementary 1, r_{UL}>0.81, p_{UL}<0.00) and only for S_2 and S_3 on LL (figure
329   supplementary 2, r=0.70, p<0.00). This result indicates that all synergy activation coefficients are
330   time-shifted by a similar amount for each participant and thus, despite the high interindividual
331   variability in EMG patterns, participants produced the same coordination pattern (i.e., 4 similar
332   synergies, produced at similar relative interval) but with delayed timings.
333
334   A weak negative correlation is observed between all UL synergy activation coefficients and RPM
335   (r_{RPM-H1}=-0.58, r_{RPM-H2}=-0.50, r_{RPM-H3}=-0.50, r_{RPM-H4}=-0.49, p<0.00) and to a lesser extent for LL
336   synergy activation coefficients and RPM (r_{RPM-H1}=-0.28, r_{RPM-H2}=-0.35, r_{RPM-H4}=-0.55, p<0.00). No
337   correlation was found between H_s and torque for UL.
338
339   **Intraindividual variability**
340   The results concerning the interindividual variability are described in table 3 and 4. Intraindividual
341   variability was inferior to interindividual variability and showed a good repeatability of kinematics,
342   torque, EMG, and synergy activation coefficients for each participant.
343

Table 3: Intradividual variability for UL. Variance Ratio (VR) and r-Pearson (r) of
Kinematics, torque, EMG patterns, synergies vectors (W_s) and synergy activation coefficients
(H_s). UL: upper limbs

344

Table 4: Intraindividual variability for LL. Variance Ratio (VR) and r-Pearson (r) of
Kinematics, torque, EMG patterns, synergies vectors (W_s) and synergy activation coefficients
(H_s). LL: lower limbs

345
346

347   # Discussion
348   The first objective of this study was to investigate whether common muscular coordination
349   processes related to mechanical output were observable during upper limbs (UL) and lower limbs
350   (LL) cycling. To this aim, muscles coordination was analyzed through synergies in relation to the
351   torque produced during cycling for both limbs. Even though the movement is strongly constrained,
352   and the relative task intensity is similar for UL and LL, the torque outputs produced by both limbs
353   showed strong differences. The results showed that cycling with the LL resulted in a reciprocal
354   contribution of one leg then the other and a production of propulsive torque during half the cycle

355 only. Cycling with the UL resulted in a different torque pattern arising from a simultaneous
356 contribution of both arms, each producing propulsive torque during most of the cycle. Despite
357 these differences in mechanical output, the same number of muscle synergies (4) were extracted
358 to account for the variations in muscle activations of 11 muscles for each limb. The simultaneous
359 analysis of the synergies related to the mechanical output showed different functional implications
360 in the movement production between UL and LL.
361
362 Our second objective was to compare the interindividual and intraindividual variability of the UL
363 and LL torque, joint kinematics, EMG, and synergy-related variables. The results showed a higher
364 variability of the UL in kinematics, torque, EMG and in muscle coordination compared to LL. More
365 precisely, the variability in EMG patterns was mainly reflected in the temporal components of
366 muscle synergies: Each synergy activation coefficient (H_s) of UL showed important time shifts
367 between participants. Nevertheless, despite this significant variability, each participant, when
368 analyzed individually, produced reproducible synergy activation coefficients.
369
370 Four synergies were extracted for both UL and LL, despite a large interindividual variability in
371 EMG patterns for UL. Our results on muscle synergy vectors showed close values of correlation
372 between participants for both limbs. The r-value obtained are lower than those obtained by De
373 Marchis 2013 or Hug 2010, which can certainly be explained by differences in the methodologies
374 used (average EMG patterns vs 25 consecutive cycles) or by the type of population chosen
375 (expert vs non-expert). It is thus reasonable to consider that the spatial constitution of the
376 synergies is shared between individuals. This indicates that the structure of synergies was robust
377 between participants and support the assumption of a spatially fixed synergies.
378 Concerning the temporal aspects of the synergies, our results showed a strong interindividual
379 variability in the EMG patterns which is reflected in the activation coefficients of the synergies, as
380 constated by several authors (Torres-Oviedo & Ting, 2007; Safavynia & Ting, 2012; De Marchis
381 et al., 2013). More specifically, each UL temporal activation coefficients showed large
382 interindividual variability, mainly resulting from differences in the onset in apparition of each
383 synergy pattern between participants rather than differences in patterns produced (table 1). These
384 results showed that same four synergy activation patterns were produced between participants,
385 with a constant interval between each synergy (Supplementary figure 1), but the expression of
386 these four synergies was highly variable in the timing of apparition during the cycle. In comparison,
387 LL synergies, particularly Syn1 and Syn2 showed low inter-individual variability which is an
388 important difference between UL and LL.
389
390 The 4 synergies extracted during LL cycling agree with the synergies described in the literature
391 in novice participants (De Marchis et al., 2013) or professional cyclists (Hug et al., 2010). S_1 and
392 S_2 were associated with the production of propulsive torque during the power phase (from top
393 dead center to bottom dead center). These two synergies strongly mobilized the hip and knee
394 extensor muscles and were therefore both involved in the same mechanical function: producing
395 propulsive torque by pushing the pedal with a leg extension (figure 4 - left). S_3 and S_4 were
396 expressed during the resistive torque production phase and may be involved to optimize the lower
397 transition and minimize the resistive torque induced by the legs weight during the flexion of the
398 limb (figure 4 – left). Importantly, a merging of S_2 and S_3 is frequently observed in literature with

expertise. S_3 is associated with tangential application of the force on the pedal at the end of the push. A merging of theses synergies is currently depicted as better orientation of the force on the crank/pedal at the end of the propulsive phase. It is therefore not surprising that both showed variability and correlation in timing of apparition. Being related, if S_2 appears earlier, S_3 logically also appears earlier. The same explanation stands for the variability observed at the level of synergy vector (W_3).

To our knowledge, a single study looked at UL muscle synergies (Botzheim et al. 2021) and observed two distinct synergies and attributed theses synergies to the two phases in the movement: pushing and pulling. If that was enough to describe bimanual coordination, it is impossible to rely on this observation to describe the mechanical output. Indeed, these authors did not used crank torque measurement nor indicates for the output power. Thanks to our methodology our study distinguishes a total of 4 synergies, three (S_1 to S_3) corresponded to propulsive torque and one (S_4) to the reduction of resistive torques. S_1 primarily involved the shoulder flexors and elbow extensor muscles meaning that the first increase in torque is related to a pushing action on the pedals. This synergy is simultaneous to shoulder antepulsion and elbow extension (figure 4 – right). S_3 involved the elbow flexors, the wrist/finger flexors, and the shoulder extensor. This synergy is simultaneous with the peak of propulsive torque production and indicates that pulling is primarily used to produce torque. This synergy is simultaneous to reduction of shoulder antepulsion and elbow flexion (i.e., reducing limb length). Our results showed that a third synergy (S_2) was involved in the production (or conservation) of propulsive torque during the transition from FH to SH. This synergy involved the wrist/finger flexors and the *latissimus dorsi*, the muscle responsible for the lowering of the arm. It seems that this synergy makes it possible to produced/conserved propulsive torque by lowering the arm in the transition from FH to SH. The simultaneous reduction of shoulder antepulsion, while elbow is still extending is in line with this explanation. Furthermore, this synergy probably takes advantage of the gravitational force to optimize the lowering action by using the weight of the arm. However, given the high relative intensity of the cycling movement, the gravitational influence is probably minimal. As for the synergies observed on LL, the synergy S_4 may be responsible for minimizing the resistive torque around the transition from SH to FH.

These results demonstrated that for a similar task demand (i.e., moving the crank at an identical relative intensity), the muscular coordination of the UL is organized around several mechanical functions (i.e., pushing, lowering, and pulling) to produce propulsive torque while the LL produce propulsive torque using a single main function (i.e., push). These differences lead to a higher mechanical efficiency for the UL pedaling (i.e., lower maximal torque and longer propulsive phase). Such differences may result from the daily use of UL in tasks of reaching, gripping, and manipulating in 3D space. The musculoskeletal system could be optimized to both extend and flex the arm. The LL are used mainly in locomotion tasks thanks to a musculoskeletal system optimized for antigravity functions (therefore pushing upward and propelling the upper body). Consequently, with torque production over a greater proportion of the pedaling cycle, which is synonymous with greater mechanical efficiency in performing the movement, UL demonstrates an important adaptation capacity to perform this movement for which our subjects and most of the population are non -expert.

443 A main difference between UL and LL is the level of variability observed. The results showed a
444 higher variability for the UL, both for torque (*performance* variability) and for EMG and muscles
445 coordination (*realization* variability). Nevertheless, when considering the variability for the UL, our
446 results showed less variability in *performance* in comparison with *realization*. Thus, a similar
447 torque pattern is produced between participants, with minor differences in shape and amplitude.
448 On the contrary, our results showed that the variability of *realization* is large and lies specifically
449 in the temporal aspects. This observation is surprising since one would have expected that
450 differences in the timing onsets of the synergies would imply similar differences in the timing
451 onsets in torques production. This suggests that there was no direct link between the variability
452 observed in muscle coordination and the variability of the resulting torque.
453 Several hypotheses can highlight these discrepancies: First, the difference in timing can be
454 explained by differences in self-selected cadence as shown by the correlation results between
455 the appearance of synergies and cadence. Nevertheless, the differences in cadence cannot
456 totally explain the temporal variability of the synergy activation patterns, especially since on LL
457 the results showed a wider range of cadence between participants and no phase shift in synergies
458 (table 5). Second, greater level of variability in the UL can also be explained by differences in
459 expertise between the UL and LL cycling. Although the participants were chosen novices for both
460 tasks, LL cycling is associated to greater expertise since it has been shown that cycling shares
461 common neural circuits with walking (Barroso et al., 2014), which ultimately induces an expertise
462 in the realization of cycling since all the participants knew how to walk. However, in the literature,
463 it has been shown during a bench press exercise that a greater inter-individual variability in
464 synergy activation patterns is synonym of expertise instead of non-experts (Kristiansen et al.,
465 2015). Thus, a difference in expertise does not seem sufficient to explain the differences in
466 realization variability observed between UL and LL.

Table 5: Cadence of each participant for UL (right) and LL (right). *LL showed more interindividual differences in cadence (ranging from 64.1±0.7 to 102.0±0.8) than UL (ranging from 71.4±0.5 to 99.6±1.3). UL: upper limbs, LL: lower limbs*

467
468 Before that conclusion can be made on the topic of expertise, further studies are needed to
469 understand whether expertise (multiple sessions of UL cycling) tends to reduce the realization
470 variability between individuals or whether individual strategies persist. Nevertheless, from our
471 results for "non-experts" (as most patients and athletes), a flexibility in the use of synergies is
472 adopted when performing the movement with UL unlike LL for which robust coordination is
473 adopted by everyone.
474

Conclusion

476 This study compared the muscles coordination during cycling with Upper Limbs (UL) and Lower
477 Limbs (LL). Torque profiles differed between UL and LL and UL EMG patterns showed a larger
478 interindividual variability than LL. Nevertheless, as already reported for LL, a functional
479 organization of the UL muscle activations do exist during UL cycling and is shared among
480 participants. UL cycling is achieved with a higher flexibly in the temporal onsets of the synergies
481 compared to LL cycling besides this higher flexibility in realization was not reflected in the
482 mechanical output. The overall results of this study could be considered when combining UL and
483 LL cycling for an assessment/rehabilitation process. Especially for UL, our results showed that an

484 individualized approach should be recommended to evaluate the coordination state of the patient
485 and to adapt the exercise parameter.

486

487

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574

Figure 1

Figure 1: Experimental set-up

Left column: Example of experimental set-up for arms (top) and legs (bottom) and schematic representation of the cycle revolution for each. The green dot represent the SH to FH transition and the red dot the FH to SH transition. FH: first half, SH: second half
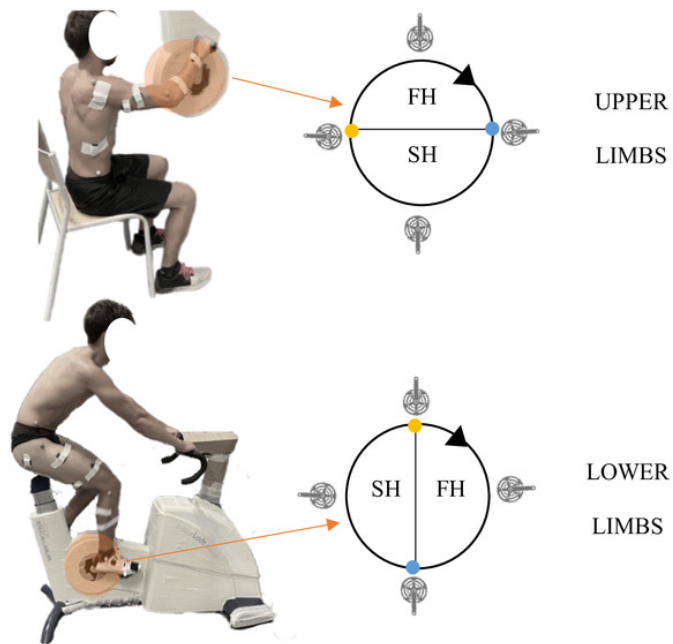
Figure 2

Figure 2: Reconstructed vs original EMG pattern

Example of reconstructed vs original EMG pattern for representative participant for lower limb muscles (left) and upper limb muscles (right).
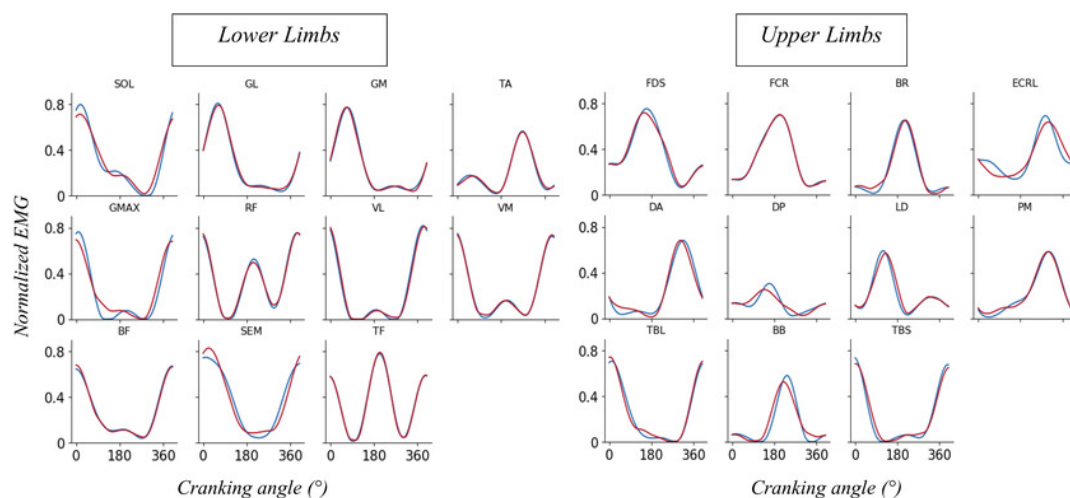
Figure 3

Figure 3: Crank torque across the cycling revolution

Mean±sd right crank torque of each subject for upper limbs (top) and lower limbs (bottom). A schematic representation of the cycling revolution. The red point illustrates the FH to SH transition, and the green point illustrates the SH to FH transition or upper transition for upper and lower limbs respectively. FH: First Half; SH: Second Half.
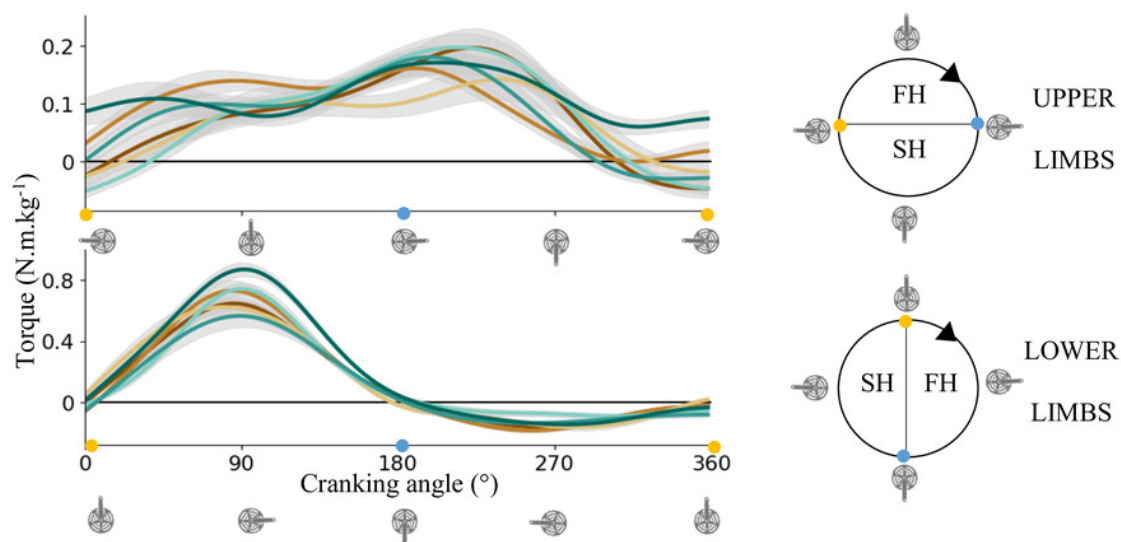
Figure 4

Figure 4: Kinematic pattern across the cycling revolution

Mean±sd angle (degree) of proximal, intermediate, and distal articulations of LL (left) and UL (right). torque of each subject for UL (top) and LL (bottom). The red point illustrates the FH to SH transition, and the green point illustrates the SH to FH transition or upper transition for upper and lower limbs respectively. FH: First Half; SH: Second Half. UL: upper limbs; LL: lower limbs
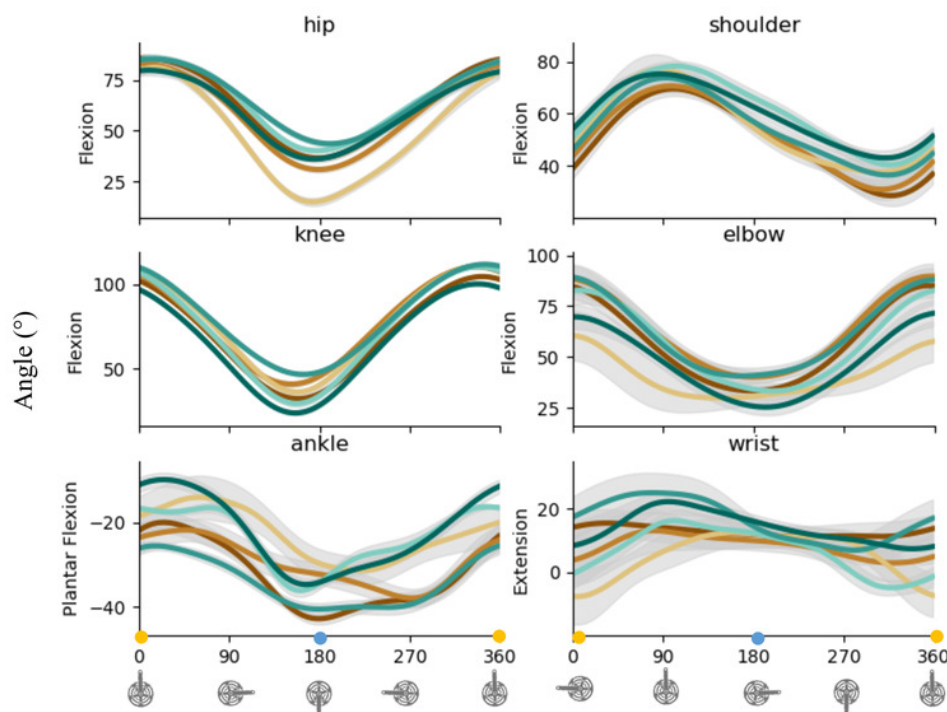
Figure 5

Figure 5: Muscle's synergy parameters and variability

Muscle synergies for LL (left) and UL (right). A-Muscle's synergies vectors (W_s) for each muscle (mean±sd). B-Mean synergy activation coefficient (H_s) for each subject. C-Boxplot of activation coefficient peak occurrences across the cycle revolution during 25 cycles for each subject (each row). The boxplot showed interindividual variability in the occurrence of the peaks for each activation coefficient: the participants 1 and 2 showed synchronous synergy occurrence, the participant 3 showed an early peak for each synergy and the participants 4, 5 and 6 showed latter peaks for each synergy. The detail of $r_{inter-H}$ showed high correlation between participants 1 and 2 ($r_{inter-1/2}$ =0.95) and between participants 4, 5 and 6 ($r_{inter-4/5/6}$>0.94). The third participant showed weak or negative correlation with all the others.
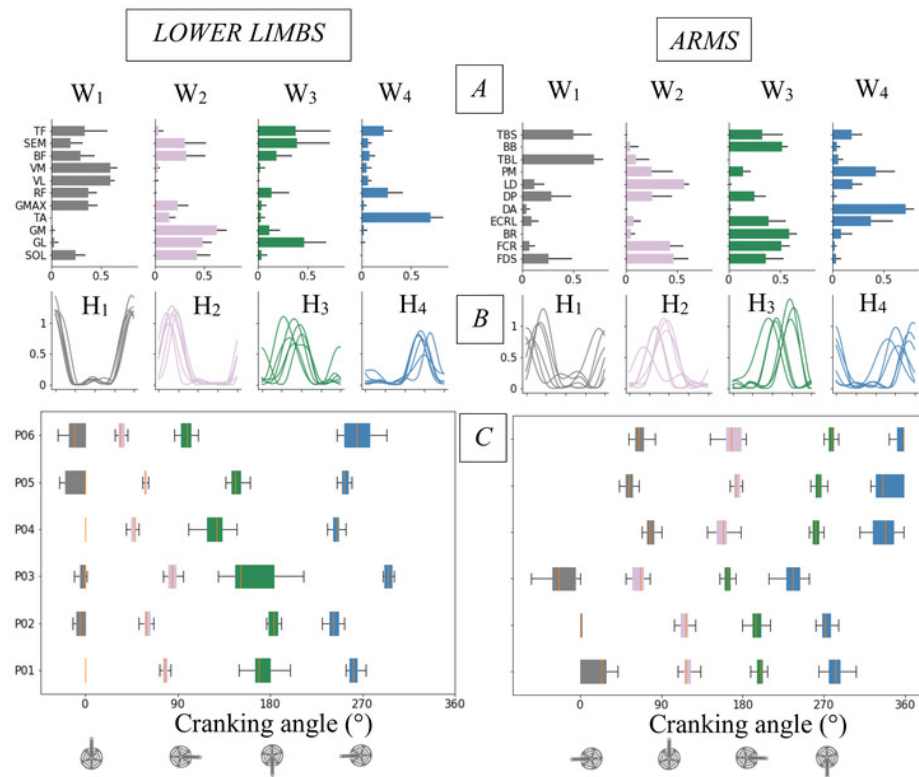
Table 1: Interindividual variability for UL

Variance Ratio (VR), r-Pearson (r), maximum value of cross-correlation function (rmax) and time lag (tmax) of Kinematics, torque, EMG patterns, synergies vectors (Ws) and synergy activation coefficients (Hs). UL: upper limbs.

Interindividual variability of upper limb variables

		VR	r	r_{max}	t_{max} %
			(mean±sd)	(mean±sd)	(mean±sd)
KINEMATICS & DYNAMICS					
Torque		0.26	0.72±0.12	0.84±0.10	2.37±2.46
Shoulder		0.12	0.93±0.03	0.99±0.01	0.87±1.01
Elbow		0.27	0.84±0.12	0.97±0.02	0.00±0.00
Wrist		0.79	0.25±0.26	0.81±0.15	11.77±9.46
EMG					
FDS		0.56	0.48±0.42	0.81±0.12	15.40±12±69
FCR		0.45	0.57±0.40	0.77±0.13	8.93±8.93
BR		0.73	0.28±0.56	0.88±0.08	16.00±11.41
ECRL		0.49	0.57±0.33	0.91±0.04	11.06±7.05
DA		0.67	0.36±0.49	0.86±0.10	13.47±10.09
DP		1.00	0.10±0.50	0.71±0.17	15.70±10.37
LD		0.67	0.32±0.49	0.87±0.07	12.50±8.12
PM		0.91	0.22±0.40	0.73±0.10	19.93±14.14
TBL		0.46	0.53±0.44	0.80±0.16	23.47±31.18
BB		0.61	0.38±0.46	0.88±0.07	13.87±9.15
TBS		0.89	0.16±0.52	0.65±0.12	15.37±14.06
Synergies	W_s		H_s		
S_0	0.75±0.17	0.61	0.40±0.48	0.80±0.15	11.80±9.81
S_1	0.71±0.11	0.41	0.46±0.42	0.90±0.06	12.60±9.70
S_2	0.75±0.12	0.70	0.30±0.52	0.89±0.08	14.57±9.99

| **S₃** | 0.75±0.17 | 0.64 | 0.38±0.46 | 0.88±0.08 | 12.87±9.22 |

Table 2: Interindividual variability for LL.

Variance Ratio (VR), r-Pearson (r), maximum value of cross-correlation function (rmax) and time lag (tmax) of Kinematics, torque, EMG patterns, synergies vectors (Ws) and synergy activation coefficients (Hs). LL: lower limbs

Interindividual variaibilty of lower limbs variables

	VR	r	r_{max}	t_{max} %
		(mean±sd)	(mean±sd)	(mean±sd)
KINEMATICS & DYNAMICS				
Torque	0.04	0.97±0.01	0.99±0.01	0.81±0.78
Hip	0.15	0.98±0.01	0.99±0.00	0.00±0.00
Knee	0.05	0.99±0.00	1.00±0.00	0.00±0.00
Ankle	0.50	0.76±0.13	0.89±0.08	2.37±2.77
EMG				
SOL	0.20	0.84 ± 0.15	0.93±0.04	3.40±3.72
GL	0.37	0.68 ± 0.26	0.91±0.05	9.87±6.10
GM	0.19	0.82 ± 0.17	0.97±0.03	5.73±3.50
TA	0.57	0.37 ± 0.45	0.84±0.10	24.93±27.13
GMAX	0.07	0.97 ± 0.02	0.97±0.02	0.00±0.00
RF	0.35	0.80 ± 0.12	0.80±0.12	0.43±1.05
VL	0.05	0.96 ± 0.03	0.96±0.03	0.10±0.39
VM	0.08	0.94 ± 0.05	0.94±0.04	0.33±0.84
BF	0.45	0.56 ± 0.32	0.77±0.14	8.90±6.84
SEM	0.45	0.64 ± 0.28	0.88±0.06	8.70±6.10
TF	0.75	0.25 ± 0.58	0.68±0.20	25.53±19.91

Synergies	W_s		H_s		
S_1	0.75±0.13	0.06	0.95±0.04	0.95±0.04	0.16±0.52
S_2	0.73±0.15	0.21	0.73±0.15	0.97±0.02	5.73±3.53
S_3	0.39±0.37	0.48	0.54±0.36	0.83±0.16	9.07±5.74

S₄	0.87±0.11	0.30	0.75±0.24	0.95±0.04	6.27±4.90

Table 3: Intradividual variability for UL.

Variance Ratio (VR) and r-Pearson (r) of Kinematics, torque, EMG patterns, synergies vectors (Ws) and synergy activation coefficients (Hs). UL: upper limbs

Upper limbs intra individual variability

	VR	r
		(mean±sd)
KINEMATICS AND DYNAMICS		
Torque	0.19	0.89±0.13
Shoulder	0.06	0.98±0.03
Elbow	0.15	0.94±0.13
Wrist	0.58	0.70±0.33
EMG		
FDS	0.21	0.90±0.09
FCR	0.17	0.91±0.08
BR	0.14	0.95±0.07
ECRL	0.24	0.89±0.12
DA	0.18	0.93±0.08
DP	0.43	0.78±0.24
LD	0.32	0.81±0.26
PM	0.37	0.82±0.20
TBL	0.11	0.95±0.05
BB	0.13	0.96±0.06
TBS	0.21	0.87±0.15
SYNERGIES		
H_1	0.11	0.95±0.06
H_2	0.12	0.94 ± 0.08
H_3	0.07	0.98 ± 0.02

H$_4$	0.13	0.95 ± 0.05

Table 4: Intradividual variability for LL.

Variance Ratio (VR) and r-Pearson (r) of Kinematics, torque, EMG patterns, synergies vectors (Ws) and synergy activation coefficients (Hs). LL: lower limbs

Lower limbs intra individual variability

	VR_{intra}	r_{intra}
		(mean±sd)
KINEMATICS AND DYNAMICS		
Torque	0.02	1.00±0.00
Hip	0.01	1.00±0.00
Knee	0.00	1.00±0.00
Ankle	0.14	0.96±0.05
EMG		
SOL	0.06	0.98±0.02
GL	0.09	0.97±0.04
GM	0.07	0.82±0.04
TA	0.32	0.95±0.30
GMAX	0.14	0.90±0.06
RF	0.23	0.98±0.13
VL	0.05	0.98±0.03
VM	0.06	0.97±0.03
BF	0.15	0.93±0.07
SEM	0.22	0.89±0.15
TF	0.21	0.87±0.18
SYNERGIES		
S_1	0.04	0.98 ± 0.02
S_2	0.05	0.98 ± 0.02

S$_3$	0.10	0.95 ± 0.05
S$_4$	0.26	0.88 ± 0.19

Table 5: Cadence of each participant for UL (right) and LL (right).

LL showed more interindividual differences in cadence (ranging from 64.1±0.7 to 102.0±0.8) than UL (ranging from 71.4±0.5 to 99.6±1.3). UL: upper limbs, LL: lower limbs

	ARMS	LEGS
	(RPM, mean±sd)	(RPM, mean±sd)
P01	90.6 ± 0.6	82.5 ± 0.3
P02	78.1 ± 1.3	89.6 ± 2.0
P03	99.6 ± 1.3	64.1 ± 0.7
P04	71.4 ± 0.5	82.1 ± 1.8
P05	92.6 ± 0.9	102.0 ± 0.8
P06	81.7 ± 0.9	80.0 ± 1.1