Catapult effect in pole vaulting: Is muscle coordination determinant?

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A B S T R A C T

This study focused on the phase between the time of straightened pole and the maximum height (HP) of vaulter and aimed at determining the catapult effect in pole vaulting on HP. Seven experienced vaulters performed 5–10 vaults recorded by two video cameras, while the surface electromyography (sEMG) activity of 10 upper limbs muscles was recorded. HP was compared with an estimated maximum height (HPest) allowing the computation of a push-off index. Muscle synergies were extracted from the sEMG activity profiles using a non-negative matrix factorization algorithm. No significant difference (p > 0.47) was found between HPest (4.64 ± 0.21 m) and HP (4.69 ± 0.23 m). Despite a high inter-individual variability in sEMG profiles, two muscle synergies were extracted for all the subjects which accounted for 96.1 ± 2.9% of the total variance. While, the synergy activation coefficients were very similar across subjects, a higher variability was found in the muscle synergy vectors. Consequently, whatever the push-off index among the pole vaulters, the athletes used different muscle groupings (i.e., muscle synergy vectors) which were activated in a similar fashion (i.e., synergy activation coefficients). Overall, these results suggested that muscle coordination adopted between the time of straightened pole and the maximum height does not have a major influence on HP.

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1. Introduction

Pole vault can be modelled in four phases: the run-up phase, the take-off phase, the pole bending phase, and the pole straightening phase. Several key times were determined within the pole straightening phase: the pole straightened (PS) and the pole release times were placed between the maximum pole bending position and the maximum height of centre of gravity of the pole vaulter (HP) (Frère et al., 2010). The energetic interaction between the pole and the athlete reveals that besides the mechanical energy of the vaulter coming from the run-up, the pole vaulter is also able to store an additional elastic energy in the pole by means of muscular work. This additional elastic energy allows the vaulter to have higher mechanical energy when crossing the bar than at take-off (Arampatzis et al., 2004). Also, it has been reported that elite pole vaulters may have different strategies to perform the vault and obtain this final mechanical energy gain, either favouring the pole bending phase or favouring the pole straightening phase. Accordingly, a recent review (Frère et al., 2010) highlighted that the actions of the shoulder muscles are of major importance in pole vaulting since they apply a bending moment on the pole and enable the elevation of the lower limbs and pelvis over the shoulders before the bar clearance.

Since previous studies have shown that the vertical velocity of the vaulter reaches its maximum around PS and decreases until HP (Gros and Kunkel, 1990; Angulo-Kinzler et al., 1994), the relationship between the final actions of the vaulter (i.e., before pole release) and the performance may be questionable. Also, the crossing of a bar placed at 6 m for the victory in the fourth IAAF World Championships in Athletics in 1993 did likely not necessitate a push-off action of the arms on the pole when the pole was fully straightened (Hommel and Houvion, 1994). Thus, one would expect that the vaulter benefits from the previous straightening of the pole to be catapulted over the bar in a relative ballistic fashion rather than performing a final push-off.

The aim of this study was to determine the catapult effect on the height of the vaulter’s centre of gravity (CG) in pole vaulting. To investigate this question we first compared the maximum height of CG of the pole vaulter to an estimated value calculated from kinematics recorded at PS. Then, we determined the coordination of the upper-limbs muscles during the vault between PS and HP. We hypothesized that the measured maximum height of the vaulter’s CG would not differ from the estimated one and that the final actions of the pole vaulter would not be correlated to the maximum
height of the vaulter’s CG despite a variability of vaulting strategy among the subjects. For the purpose of this study, we recorded kinematics and surface electromyography (sEMG) activity of 10 upper-limb muscles. In addition to a classical analysis of the sEMG activity patterns, we used a non-negative matrix factorization algorithm to identify muscle synergies. The use of this latter analysis aimed at providing additional insights about the muscle coordination strategies used by the subjects (Ting and Chvatal, 2010; Hug, 2011).

2. Materials and methods

2.1. Population

Seven experienced pole vaulters (height: 180 ± 6 cm, weight: 74 ± 6 kg) participated in this study. The best performance of the subjects varied from 4.85 to 5.35 m (79–87% of the current world record, respectively). Each athlete performed between 5 and 10 vaults at 90% of their best performance. Finally, three to five valid vaults per athlete were analyzed (n = 24). A written consent was obtained from each participant prior to testing in accordance with the Helsinki declaration and the ethics approval was obtained from the local ethics research committee.

2.2. Experimental setup and motion capture

The motion capture was organized according to the “2d-center of mass” procedure of Schade et al. (2000). The vaults were recorded at 50 fields/s by two video cameras (Panasonic NV-GS17, Japan) synchronized with a flashlight. One camera recorded the movement from the second last stride to approximately the maximum pole bend position. The other camera recorded the succeeding movement up to bar clearance. Each camera was positioned at 90° to the main plane of movement. The calibration square was 4 × 4 m and the origin of the inertial coordinate system was located above the deepest point of the planting box at ground level in the middle of the run up path. The x-axis was defined to be the horizontal axis in the main plane of movement. The y-axis was defined as the vertical one.

To reconstruct a multi-segments model of the athlete, markers made of adhesive strips were placed on defined body marks. The digitization of body marks was performed manually using SIMI Motion© software (SIMIT Reality Motion Systems GmbH, Unterschleissheim, Germany): for both lower extremities the tip of the foot, heel, ankle, knee and hip joints, for both upper extremities the hand, wrist, elbow and shoulder joints and for the head C7-vertebrae and the middle of the head. The trunk included both shoulders and both hips. The model was composed of the following 14 segments: arms, forearms, hands, trunk, thighs, legs and feet. The masses and moments of inertia of different segments were calculated using an anthropometric table (de Leva, 1996).

This experimental setup had inherent limitations, such as the accuracy of motion capture or loss of markers at certain times of the vault due to the positions of the cameras. The resolution of cameras (720 × 576 pixels) and the manual digitization of the markers led to an accuracy of ±2 cm for each marker along the horizontal and vertical axis.

2.3. Kinematics

From the PS time, the vertical position of the vaulter’s CG was calculated with the following equation:

\[ y(t) = -\frac{1}{2} g \cdot t^2 + v \cdot \sin \theta \cdot t + H_{CG} \]

where \( v \) is the resultant velocity of the CG at PS (m s\(^{-1}\)), \( \theta \) the angle between the horizontal axis and \( v \) at PS (°), \( g \) the acceleration due to gravity (9.81 m s\(^{-2}\)), and \( H_{CG} \) the CG position of the vaulter along the vertical axis at PS (m) (Fig. 1). Then, the maximum (H\(_{est}\)) value of the calculated vertical position of the vaulter’s CG was retained.

Applying this formula at PS to estimate the maximum height of the vaulter’s CG, while the vaulter was still in contact with his pole, corresponded to an estimation without considering the action of the upper limbs of the athlete between PS and HP. Therefore, if the estimated height was lower than the measured final height, it signified that the trajectory of the vaulter’s CG was modified with a gain of height by the actions of the athlete on the pole. Conversely, if the estimated height was greater than or equal to the measured final height of the vaulter’s CG, it signified that there was a negative or null influence of the vaulter’s actions on the trajectory of the CG. As a representation of this influence of the vaulter’s action on the trajectory of the CG, a push-off index was calculated using the measured final height of the vaulter’s CG (HP) as a percentage of the estimated height (H\(_{est}\)). Thus, a positive push-off index revealed the gain of vertical height relative to HP, a null index revealed no difference between HP and H\(_{est}\), and a negative index revealed a loss in vertical height relative to H\(_{est}\).

2.4. Electromyography

Surface EMG activity from five muscles was recorded in both the dominant (D) and non-dominant (ND) upper limb: deltoideus pars clavicularis (DC), infraspinatus (IS), biceps brachii (BB), triceps brachii caput laterale (TB), and latissimus dorsi (LD). According to Frère et al. (2008), the dominant side corresponded to the upper limb of the upper handgrip on the pole while the non-dominant side corresponded to the upper limb of the lower handgrip on the pole. The sEMG recordings were made using self-adhesive Ag/AgCl pairs of electrodes (Dual electrodes, Noraxon USA Inc., Scottsdale, Arizona, USA). The diameter of each area of conductivity was 10 mm while the distance between electrodes was 20 mm. The electrodes were placed longitudinally with respect to the underlying muscle fiber arrangement (De Luca, 1997) and were...
located according to the recommendations of SENIAM (Surface EMG for Non-Invasive Assessment of Muscles) (Hermens et al., 2000). Before the electrodes were applied, the skin was shaved and cleaned with alcohol to minimize impedance. The wires connected to the electrodes were well secured with adhesive tape to avoid movement-induced artifacts and loosening. The sEMG signal was amplified (gain of 1000 and bandwidth of 10–700 Hz; Biovision, Wehrheim, Germany) and digitized at a sampling rate of 2500 Hz by a personal digital assistant (PDA) computer HP iPAQ5500 (Hewlett-Packard, Palo Alto, CA, USA) with an A/D-card PCM16 (Superlocis, Waltham, MA, USA). The PDA was placed in a protective box attached to the thigh of the athlete allowing both reduce discomfort during the vault and ensure a safe landing. The whole device was placed at the end of the warm-up. All warm-up jumps were performed with the placed sEMG electrodes and the empty protective box, allowing the athletes to be accustomed to the portable system. After crossing the bar, the vaulter fell on the landing mats. This fall on mats induced an artifact in the sEMG signal which served as starting point for a backward synchronisation with the video. Such synchronisation had an accuracy of one half of the video field (i.e., 0.01 s).

2.5. Processing of surface electromyography signals

The sEMG processing was performed across the frequency 19–395 Hz using an sEMG specific wavelet analysis (Frère et al., 2011) based on a wavelets filter bank with a non-linear scale function (von Tscharner, 2000) from a previously developed algorithm (Torrence and Compo, 1998) available at URL: http://paos.colorado.edu/research/wavelets. First, the signals were quantified by their intensities between the take-off and the highest vertical position of the vaulter’s CG for each pole vault. The total intensity of the sEMG signal was a positive envelope which quantified the signal and was equivalent to twice the square of the root mean square (Frère et al., 2011). These sEMG intensities (i.e., sEMG envelopes) were normalized by their respective maximum value over the complete pole vault, thereby obtaining values between 0 and 1. Then, the sEMG intensity curves were filtered using a 4th order low pass Butterworth filter with a cut-off frequency of 5 Hz with zero lag. Finally, solely the portions of the sEMG intensity curves corresponding to the final part of the vault (between PS and HP) were retained and were interpolated to obtain a time-scale normalization of 200 time points.

The coordination strategies of the ten upper-limbs muscles were studied by using non-negative matrix factorization (NMF) algorithm. As the principal component analysis, the NMF is capable of decomposing large datasets of sEMG data into the summed activation of just a few muscle synergies or modules (Ting and Chvatal, 2010; Hug, 2011). Regarding the physiological interpretations, the non-negative constraint in NMF may provide closer meaningful results to the neural and muscle output than in principal component analysis (Ting and Chvatal, 2010). It has been proposed that the central nervous system produced movement through the flexible combination of these muscle synergies (for a review, see Tresco and Jarc, 2009). Thus, they provided an attractive simplified strategy for the control of complex movements because they reduced the number of output patterns that the nervous system must specify for a large number of muscles (Bizzi et al., 2008). The NMF algorithm used to identify muscle synergies possesses two components: a fixed component (named “muscle synergy vectors” or “muscle weightings”), which represents the relative weighting of each muscle within each synergy, and, a temporal component (named “synergy activation coefficient” or “activation timing profile”), which represents the relative activation of muscle synergies. As previously done with sEMG data recorded during cyclic activities (Hug et al., 2010, 2011; Turpin et al., 2011), the Lee and Seung algorithm (2001) was used to perform the NMF. The residual Frobenius norm between the initial matrix and its decomposition was minimized by matrix factorization, given as:

$$E = WC + e$$

$$\min_{W, C} \|E - WC\|_{FRO}$$

where \(E\) was a \(p\)-by-\(n\) initial matrix (\(p = \text{number of muscles and } n = \text{number of time points}\)), \(W\) was a \(p\)-by-\(s\) matrix (\(s = \text{number of synergies}\)), \(C\) was a \(s\)-by-\(n\) matrix and \(e\) was a \(p\)-by-\(n\) matrix in Eq. 2. In Eq. 3, \(\|\cdot\|_\text{FRO}\) established the Frobenius norm, \(W\) represented the muscle synergy vectors (or muscle weightings) matrix, \(C\) was the synergy activation coefficients (or activation timing profile) matrix. The matrix \(e\) was the residual error matrix. The algorithm was based on iterative updates of an initial random guess of \(W\) and \(C\) that converged to a local optimal matrix factorization [see (Lee and Seung, 2001) for more details]. To avoid local minima, the algorithm was repeated 10 times for each trial. The lowest cost solution was kept (i.e., minimized squared error between original and reconstructed EMG patterns). In the present study, the NMF was performed for each pole vault. Thus, the initial matrix \(E\) consisted of a 10-row and 200-column matrix. For each pole vault and each subject, the analysis was iterated by varying the number of synergies between 1 and 10 and then the least number of muscle synergies that accounted for \(\geq 90\%\) of variance accounted for (VAF) was selected (Torres-Oviedo et al., 2006; Hug et al., 2010, 2011). The muscle synergy vectors were normalized by their maximum under the synergy to which they belong (Hug et al., 2010). Then, the matrices \(W\) and \(C\) were averaged for each subject.

2.6. Statistics

All statistical tests were performed with MATLAB® (The MathWorks Inc., Natick, MA, USA). The conditions for the use of parametric tests being affected (normal distributions and homogeneity of variances), the Wilcoxon rank test was used to compare the values of the estimated maximum height of the vaulter’s CG with those measured. The Kruskal–Wallis test (non-parametric one-way ANOVA) was used to determine if the push-off index of the pole vault varied significantly between the athletes who participated in this study. Single and multiple linear regression models were used to determine how much the kinematic parameters at PS (\(H_{CG}, \nu, \theta\)) are predictive of the maximum vertical position of the vaulter’s CG.

Pairwise comparisons of the sEMG intensity profiles and synergy activation coefficients were assessed using two criteria: the \(r_{\text{max}}\) coefficient and lag time (Hug et al., 2011; Turpin et al., 2011). \(r_{\text{max}}\) corresponded to the correlation coefficient at the maximum of the cross-correlation function obtained using the Matlab xcorr function for centered data (option = ‘coeff’) and gave an indication on the similarity of the waveforms (i.e., the sEMG intensity profiles or synergy activation coefficients). The lag times corresponded to the time shift between the two waveforms at \(r_{\text{max}}\). Pearson’s correlation coefficient (\(r\)) was used as a similarity criterion for the muscle synergy vectors. The threshold of significance was set at \(p < 0.05\).

3. Results

3.1. Height of the vaulter’s CG estimation and push-off index

The vertical velocity of the vaulter’s CG decreased between PS and HP (Fig. 2). On average, the measured maximum height of the vaulter’s CG was not significantly (\(p > 0.47\)) higher than the
estimated height (Table 1). The push-off index representing the actions of the vaulter at the end of the vault varied between −3.2% and 7.8% among all vaults measured (n = 24). A significant variation (p < 0.05) in the push-off index among the athletes was found, reflecting the different techniques used to cross the bar regardless of the level of performance of the pole vaulters.

The linear regression determined that 70% of HP was explained by the estimated maximum height of the vaulter’s CG at PS (HP_{est}). The angle $\theta$ was the only one kinematic parameter at PS to significantly predict HP, while the multiple linear regression indicated that HP was explained at 88% when taking together H_{CG}, $v$, and $\theta$ (Table 2). Also, the determination coefficient between the push-off index and the measured maximum height of the vaulter’s CG was not significant.

### 3.2. sEMG profiles

The pairwise comparison of the sEMG patterns across the seven pole vaulters (Fig. 3) revealed moderate to high $r_{\text{max}}$ values (from 0.59 to 0.96) while the absolute lag times were up to 22.5% of the phase between PS and HP (Table 3).

### 3.3. Muscle synergies

Using the criteria previously described, two muscle synergies were extracted, which accounting for 96.1 ± 2.9% of the total VAF. Similar to the sEMG intensity curves, the muscle synergy vectors (W) showed high inter-individual variability across the pole vaulters (Fig. 4). More precisely, the median value of the Pearson’s correlation coefficient was 0.35 (ranged from −0.23 to 0.72) for synergy #1 and 0.42 (ranged from −0.38 to 0.91) for synergy #2. Since the $r_{\text{max}}$ values were high and lag times were low (Table 3), the synergy activation coefficients (C) were consistent across the seven pole vaulters. Overall, these results indicate that the subjects used different muscle groupings (i.e., muscle synergy vectors), but that they activated them in a similar fashion (i.e., synergy activation coefficients).

### 4. Discussion

This study determined that a pole vaulter is mainly catapulted from the pole between PS and HP, despite different vaulting strategies across the subjects. As previously reported in the literature (Gros and Kunkel, 1990; Angulo-Kinzler et al., 1994), the vertical velocity of the vaulter’s CG decreased after PS and until HP (Fig. 2). Therefore, computing a push-off index based on a free flight movement from PS time appeared coherent with the nature of the captured movement in this phase of the vault. The influence of final athlete’s actions on the pole vault was analyzed by comparing the estimated maximum height of the vaulter’s CG (HP_{est}) with the measured maximum height (HP). This process has shown that on average, the estimated maximum height of CG of the vaulter was not significantly lower than the measured one (Table 1). Also, the regression analysis (Table 2) confirmed that the final actions of the vaulter had no significant influence on HP, but demonstrated that the catapult effect of the pole on the athlete was crucial to predict HP. The overall results about the kinematics of the CG of the vaulter minimized the action of upper limbs in this phase of the vault (between PS and HP) and implied that the highest vertical position of the vaulter’s CG depended mainly on previous actions of the vaulter, especially during the pole bending phase. These earlier actions would then develop favorable conditions for performance in subsequent phases, especially after the full vertical straightening of the pole.

To extract muscle synergies during the last phase of the vault, the non-negative matrix factorization was applied to the sEMG dataset. Hug et al. (2010) recently showed that similar muscle synergies are used by trained cyclists during pedaling despite inter-individual variability of the initial sEMG patterns. In this study the pole vaulters presented two similar temporal components (i.e., synergy activation coefficients); however, the muscle synergies (i.e., muscle synergy vectors) remained highly variable across the individuals (Fig. 4). These two temporal components may have a

### Table 1

Kinematics of the vaulter’s CG. Data are medians (S.D.) for each pole vaulter.

<table>
<thead>
<tr>
<th>Subjects (personal record, in m)</th>
<th>Subject #1 (5.00)</th>
<th>Subject #2 (4.85)</th>
<th>Subject #3 (5.10)</th>
<th>Subject #4 (5.35)</th>
<th>Subject #5 (4.90)</th>
<th>Subject #6 (5.25)</th>
<th>Subject #7 (5.30)</th>
<th>Mean of the group</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP (m)</td>
<td>4.43 (0.16)</td>
<td>4.75 (0.14)</td>
<td>4.74 (0.08)</td>
<td>5.13 (0.06)</td>
<td>4.45 (0.16)</td>
<td>4.64 (0.06)</td>
<td>4.67 (0.12)</td>
<td>4.69 (0.23)</td>
</tr>
<tr>
<td>HP_{est} (m)</td>
<td>4.36 (0.14)</td>
<td>4.49 (0.19)</td>
<td>4.70 (0.14)</td>
<td>4.97 (0.15)</td>
<td>4.46 (0.26)</td>
<td>4.74 (0.14)</td>
<td>4.74 (0.08)</td>
<td>4.64 (0.21)</td>
</tr>
<tr>
<td>Push-off index (%)</td>
<td>2.24 (2.60)</td>
<td>5.92 (1.87)</td>
<td>0.60 (1.28)</td>
<td>2.00 (2.98)</td>
<td>-0.18 (2.38)</td>
<td>-2.02 (1.81)</td>
<td>-0.88 (1.23)</td>
<td>1.10 (2.61)</td>
</tr>
<tr>
<td>$H_{CG}$ at PS (m)</td>
<td>4.07 (0.15)</td>
<td>3.73 (0.06)</td>
<td>4.16 (0.07)</td>
<td>4.12 (0.03)</td>
<td>3.98 (0.16)</td>
<td>4.07 (0.07)</td>
<td>4.06 (0.14)</td>
<td>4.03 (0.14)</td>
</tr>
<tr>
<td>$v$ of CG at PS (m/s$^{-1}$)</td>
<td>3.19 (0.37)</td>
<td>4.02 (0.44)</td>
<td>3.68 (0.13)</td>
<td>4.40 (0.49)</td>
<td>3.83 (0.34)</td>
<td>4.25 (0.21)</td>
<td>4.29 (0.40)</td>
<td>3.95 (0.42)</td>
</tr>
<tr>
<td>Angle $\theta$ at PS (°)</td>
<td>50.0 (8.31)</td>
<td>69.5 (4.74)</td>
<td>60.9 (9.71)</td>
<td>68.1 (5.00)</td>
<td>58.3 (3.51)</td>
<td>57.6 (0.82)</td>
<td>59.5 (3.86)</td>
<td>60.6 (6.60)</td>
</tr>
</tbody>
</table>

HP: measured maximum height of the vaulter’s CG; HP_{est}: estimated maximum height of the vaulter’s CG; $H_{CG}$: measured height of the vaulter’s CG at PS; $v$: resultant velocity of the vaulter’s CG; $\theta$: orientation of the resultant velocity of the vaulter’s CG with the horizontal axis.
functional significance in relationship with the successive pole release of both hands. Indeed, all the vaulters released the pole first by the non-dominant hand then by the dominant hand, while the first component had its peak just after PS followed by the second one at around 60% of the PS-HP phase of the vault. However, the muscle synergy vectors were specific to each pole vaulter since they used different muscle groupings to perform this bimanual pole release. To our knowledge, these non-negative matrix factorization outcomes (i.e., similar temporal components and different muscle synergies) have been little reported. Recently, Gizzi et al. (2011) compared the muscles synergies during locomotion between subacute stroke patients and controls and found that stroke patients had different muscle synergy vectors from those observed in healthy patients, despite similar functional temporal components. The presence of this similarity between healthy and stroke patients substantiated the evidence of spinal neural networks.

Table 2
Regression equations and determination coefficients.

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>Determination coefficient</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP = HPest x 0.93 + 0.39</td>
<td>R² = 0.70</td>
<td>0.02</td>
</tr>
<tr>
<td>HP = HCG x 0.21 + 3.86</td>
<td>R² = 0.02</td>
<td>0.80</td>
</tr>
<tr>
<td>HP = v x 0.36 + 3.25</td>
<td>R² = 0.44</td>
<td>0.11</td>
</tr>
<tr>
<td>HP = θ x 0.03 + 3.00</td>
<td>R² = 0.62</td>
<td>0.04</td>
</tr>
<tr>
<td>HP = Push-off index x 0.02 + 4.66</td>
<td>R² = 0.06</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Multiple linear regression equation

<table>
<thead>
<tr>
<th>Determination coefficient</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP = HCG x 0.93 + v x 0.02 + θ x 0.04 - 1.29</td>
<td>R² = 0.88</td>
</tr>
</tbody>
</table>

Note: HP: measured maximum height of the vaulter’s CG; HPest: estimated maximum height of the vaulter’s CG; HCG: measured height of the vaulter’s CG at PS; v: resultant velocity of the vaulter’s CG; θ: orientation of the resultant velocity of the vaulter’s CG with the horizontal axis.

Table 3
Interindividual variability of the initial EMG patterns and synergy activation coefficients.

<table>
<thead>
<tr>
<th>EMG envelopes</th>
<th>rmax</th>
<th>Lag (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDND</td>
<td>0.89 (0.81–0.98)</td>
<td>0.00 (–27.0 to 50.0)</td>
</tr>
<tr>
<td>TBND</td>
<td>0.59 (0.27–0.97)</td>
<td>0.00 (–72.0 to 51.0)</td>
</tr>
<tr>
<td>BBND</td>
<td>0.91 (0.73–0.99)</td>
<td>4.00 (–10.0 to 14.0)</td>
</tr>
<tr>
<td>ISND</td>
<td>0.85 (0.64–0.98)</td>
<td>0.00 (–39.5 to 0.00)</td>
</tr>
<tr>
<td>DCDN</td>
<td>0.84 (0.52–0.99)</td>
<td>0.50 (–51.5 to 39.3)</td>
</tr>
<tr>
<td>LDp</td>
<td>0.81 (0.59–0.98)</td>
<td>21.5 (–52.5 to 71.0)</td>
</tr>
<tr>
<td>TBP</td>
<td>0.92 (0.80–0.99)</td>
<td>10.5 (–35.0 to 37.0)</td>
</tr>
<tr>
<td>BBp</td>
<td>0.96 (0.87–0.99)</td>
<td>0.00 (0.00–0.00)</td>
</tr>
<tr>
<td>ISP</td>
<td>0.89 (0.72–0.99)</td>
<td>22.5 (–54.5 to 58.0)</td>
</tr>
<tr>
<td>DCp</td>
<td>0.93 (0.74–0.98)</td>
<td>5.00 (–40.0 to 33.0)</td>
</tr>
<tr>
<td>Synergy activation coefficients #1</td>
<td>0.96 (0.88–0.99)</td>
<td>0.00 (0.00–0.00)</td>
</tr>
<tr>
<td>#2</td>
<td>0.98 (0.93–1.00)</td>
<td>0.00 (–18.5 to 13.0)</td>
</tr>
</tbody>
</table>

Note: values are medians (range). rmax: cross-correlation coefficient; lag: lag time in percentage of the final phase of the vault; LD: latissimus dorsi; TB: triceps brachii; BB: biceps brachii; IS: infraspinatus; DC: deltoideus pars clavicularis; ND suffix: non-dominant; D suffix: dominant. Lags are calculated as the lag-times that maximize the cross-correlation function. A positive bias indicates that the second pattern is shifted earlier in the cycle relative to the first pattern. The median values of the lag are calculated from the absolute values of the distribution of the lags.

Fig. 3. sEMG intensity profiles for the 10 upper-limb muscles obtained in 7 pole vaulters. Each profile represents an averaged individual sEMG pattern between the pole straightening (PS) time and the highest vertical position of the vaulter’s CG (HP) expressed in percentage. The bold black line indicates the mean profile across the seven subjects. LD: latissimus dorsi; TB: triceps brachii; BB: biceps brachii; IS: infraspinatus; DC: deltoideus pars clavicularis; ND suffix: non-dominant; D suffix: dominant. For the clarity of the figure, the sEMG intensity curves are normalized to one. (For colour interpretation, the reader is referred to the online version of this article).
(i.e., central pattern generators) which may be the origin of invariant activation signals to control the movement. In this way, the present results would suggest a possible central motor control of the upper-limb muscle coordination in the last phase of the vault, even if different muscle synergy vectors were determined across the athletes. To our knowledge, there is no study that has examined the muscle synergies of the upper-limb muscles when they are activated to support the body (e.g., handstand position). As a consequence, further studies are needed to analyze the muscle coordination of the upper-limbs during such complex movements in a controlled environment to provide (or not) new evidence of such motor control as found in the present study.

Also, it appeared that the pole vaulters could be classified from their push-off index. Based on this index, the strategy during the last phase of the vault would be highlighted by determining athletes who had a gain in height and those who had no gain. This kinematic classification in confrontation with the weightings of the muscle synergies did not provide clear evidence of a relationship between the push-off action and the muscular coordination. This result thus agreed with the above statement about the strong relationship between the maximum height of the vaulter’s CG and the kinematic variables at PS. Consequently, the present study confirmed and refined the hypothesis regarding the relevant upper-body muscles activity on the pole vault performance.

Shoulder muscles activations are a relevant factor on pole vault performance to actively bend the pole and store additional elastic energy in it (Hubbard, 1980; McGinnis and Bergman, 1986; Arampatzis et al., 2004; Morlier and Mesnard, 2007), while a reversal of the body parallel to the pole will improve the vertical velocity of the vaulter’s CG rather than a final push on the pole. However, it should be kept in mind that even if the present study focused on the last phase of the vault, the actions of the athlete at the end of the vault may be the consequence of previous activity occurring in the earlier phases of the vault. In this way, it was decided to normalize the sEMG intensity to the maximum value of the full vault rather than to normalize it to the maximum

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**Fig. 4.** Synergy activation coefficients (C – solid lines in different colors) and muscle synergy vectors (W – bar graphs in different colors) across the seven subjects for the two extracted synergies. The synergy activation coefficients are expressed as a function of the percentage of PS-to-HP phase of the vault. The mean synergy activation coefficient over all subjects is represented by the bold black line. LD: latissimus dorsi; TB: triceps brachii; BB: biceps brachii; IS: infraspinatus; DC: deltoideus pars clavicularis; ND suffix: non-dominant; D suffix: dominant. (For colour interpretation, the reader is referred to the online version of this article).
value. This could lead to high differences in amplitude across the sEMG intensity curves in the last phase of the vault. Also, the sEMG recordings only gave information about the pattern of muscle activity and not the degree of muscle activity (linked to the force production). Moreover, the recordings were limited to surface muscles while other deeper muscles might be solicited to perform the push-off action on the pole. However, the ability to investigate these deeper muscles by intramuscular electromyography was highly compromised in such ecological and perilous situation. It should be noted that the vaulter should cross a bar placed at 90% of their personal best. This limitation was imposed to take into account the inconvenience caused by the entire sEMG device. Further due to the lower height of the jumps, the athletes used a less rigid pole than regular used in competition. This could affect the vertical return of the pole vaulter and cause a lower vertical velocity of CG at PS than in competition. Therefore the muscle activation might be altered to compensate for this loss in vertical velocity in comparison with conditions of vaults during competition.

Also, the use of a 2d motion capture from video cameras recording at 50 fields/s may be a limitation since the longitudinal rotation experienced by the athlete in this phase of the vault implied movements in three dimensions. Thus, the horizontal and vertical positions of the vaulter's CG might be over- or under-estimated, affecting the calculated push-off index. However, recording the vault at 50 Hz might not affect the results since such rate frequency was available to compute the mechanical energy of the vaulter (based on the complete body digitalization or on the CG positions) (Schade et al., 2000, 2004, 2006; Arampatzis et al., 2004) or available to compute the kinetics of the vault (Motl and Mesnard, 2007). It seems that recording the movement at 50 Hz did not limit the main results of this study: the final height of the vaulter's CG was related to kinematics data at PS and not affected by particular muscle coordination. Nevertheless, further studies are needed to present the result presents by simultaneously using 3d motion capture at higher rate and better resolution (e.g., optoelectronic system), recording the force applied on the pole (e.g., force plate on the take-off box), and investigating other muscles (e.g., pectoralis major, deltoideus pars spinalis and other muscles).

5. Conclusion

This study showed that the maximum height of the vaulter's CG in pole vault is not likely influenced by final actions of the athlete on the pole before bar clearance. If the actions of upper limb muscles were known to be critical about the performance in pole vault, it appeared that these actions were major in phases before the full straightened pole, i.e., the take-off phase and pole bending phase. These earlier phases must help to create favorable conditions for the completion of the vault, with a focus on vaulter's vertical velocity by using a reversal body position as parallel as possible to the longitudinal axis of the pole.

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References


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