ELSEVIER

Neuroscience Letters 242 (1998) 135–138

Neuroscience Letters

Multi-joint coordination strategies for straightening up movement in humans

Guy Cheron[a,*], Ana Bengoetxea[a], Bernard Dan[a], Jean-Philippe Draye[b]

[a]*Laboratory of Movement Biomechanics, ISEPK, Université Libre de Bruxelles, Avenue P. Héger, CP168, 1050 Brussels, Belgium*
[b]*Parallel Information Processing Laboratory of the Faculté Polytechnique de Mons, Mons, Belgium*

Received 8 December 1997; received in revised form 29 December 1997; accepted 3 January 1998

Abstract

Complex movement execution theoretically involves numerous biomechanical degrees of freedom, leading to the concept of redundancy. The kinematics and kinetics of rapid straightening up movement from the squatting position were analysed with the optoelectronic ELITE system in 14 subjects. We found multiple acceleration and deceleration peaks for the hip, knee and ankle joints during the early extension phase of the movement. In order to test the temporal coordination between the angular acceleration of these joints, conjugate crosscorrelation functions (CCF) between each set of two variables were calculated. We found a bimodal distribution of the maximum CCF in positive and negative values suggesting the existence of two distinct strategies, the in-phase and the out-of-phase strategy for each pair of joints. The hip and knee coordination strategies (in- or out-of-phase) were well conserved in each subject for repetitive movements. Combination of joint pair strategies was more reproducible for the hip-knee/knee-ankle pair than for the other combinations, suggesting that the straightening up strategies are organised around the knee. We conclude that mastering of the redundancy problem can be realised by using coordination strategies characterised by opposed joint acceleration patterns. © 1998 Published by Elsevier Science Ireland Ltd.

Keywords: Posture; Motor strategies; Coordination; Kinematics; Kinetics

Any motor act performed in everyday life can be realised in more than one way. This is the result of a complex interaction between the neural control processing of the musculoskeletal system, which is endowed with redundant degrees of freedom [2] and biomechanical constraints imposed by a variable environment.

Considerable variability in kinetic and kinematic patterns across subjects can be seen for simple movements, such as response to stance perturbation [8–11] or upper trunk bending [13], and for more complex movements, such as walking [4,12] or jumping [3]. However, all of these studies demonstrate the emergence of a limited number of motor strategies for each type of movement. The present study has attempted to assess the motor strategies used by freely behaving subjects for rapid self-paced straightening-up movement from the squatting position. The main questions addressed were: (1) can different coordination strategies of joint accelerations be defined?; (2) which groups of joints show consistent coordinated patterns?; (3) are the strategies consistent in each subject for repetitive movements?

Informed consent was received from 14 healthy subjects (10 females, four males) aged between 21 and 40 years (mean age 28 years). The experiment were performed in accordance with the ethical standards of the Declaration of Helsinki 1964. The subjects were in a stable squatting position with their arms extended horizontally in the sagittal plane. They were asked to straighten up as fast as possible at their own pace, maintaining their arms extended forwards. Five trials were recorded and analysed for each subject.

Movements were recorded and analysed using the optoelectronic ELITE system [7]. This system consists of two CCD-cameras detecting retro-reflective markers using a sampling rate of 100 Hz. The detailed experimental procedure can be found in a previous work [5]. In order to test the temporal coordination between the hip, knee and ankle angular accelerations, conjugate cross-correlation functions

* Corresponding author. Tel.: +32 2 650217; fax: +32 2 6503745; e-mail: gcheron@resulb.ac.be

0304-3940/98/$19.00 © 1998 Published by Elsevier Science Ireland Ltd. All rights reserved
PII S0304-3940(98)00053-6

(CCF) [1] between each set of two variables were calculated. The span of time lags or leads were analysed for a time window (T) starting at the onset of movement and ending at the maximum peak of angular velocity. The CCF between two functions $h(t)$ and $k(t)$ is defined as:

$$\mathrm{CCF}_{\mathrm{hk}}(t) = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} h(t)k(t-\tau)\mathrm{d}t$$

where τ is the lag between the two functions. With a sampling rate of 100 Hz, points at lag τ of 1 correspond to a temporal lag of 10 ms. When the signals $h(t)$ and $k(t)$ are statistically correlated their CCF displays a peak (a significant CCF maximum) or a trough (a significant CCF minimum) at the abscissa τ^*. A positive value of τ^* means that $h(t)$ moves τ^* ms before k(t). A negative value of τ^* means that $h(t)$ moves τ^* ms after $k(t)$. A significant CCF peak means that $h(t)$ and $k(t)$ vary in the same direction (increase or decrease); this situation defines an in-phase strategy (denoted IN). On the other hand, a significant CCF trough means that both functions vary in opposite directions; it defines an out-of phase strategy (denoted OUT). If $h(t)$ and $k(t)$ have the same fundamental period, CCF is a periodic function with the same period as both signals. The determination of the strategy represented by the CCF peak must be done within half a period of the cross-correlation function; i.e. a quarter of period before and after $\tau = 0$. This statement is very important in the case of the angular acceleration series under study: their power spectrum density function contained a peak at roughly 3 Hz. The category of the strategy is determined using the sign of the absolute extremum of the CCF in a temporal window of $-80 \leq \tau \leq +80$ ms. The CCFs were computed using the time series analysis software of Statistica.

In order to assess the reproducibility of strategies, an individual scoring function (ISF) was defined for each subject and each pair of biarticular relationships (hip-knee (HK), knee-ankle (KA) and hip-ankle (HA)). Four, three or two points were attributed when the same combination of strategies occurred for five, four or three movements performed by a particular subject, respectively. One point was attributed when only two strategies were identical. This allocation of points was used because five movements cannot be executed with more than four combinations of strategies: IN-IN, IN-OUT, OUT-IN, OUT-OUT. In order to assess whether our experimental population exhibited a significant reproducibility, we compared observed ISFs with the ones produced by a fictive population whose members display totally random strategies. For a particular fictive member (random strategies), the probability (P) that his five different movements present the same strategy is given by:

$$P(\text{five identical strategies}) = \frac{C_4^1}{4^5} = \frac{1}{256} \text{ with } C_{\mathrm{m}}^{\mathrm{n}} = \frac{m!}{n!(m-n)!}$$

The other three probabilities are given respectively by:

$$P(\text{four identical strategies}) = 2.C_4^2.\frac{5!}{4!} = \frac{15}{256}$$

$$P(\text{three identical strategies}) = 3.C_4^3.\frac{5!}{3!} + 2.C_4^2\frac{5!}{3!.2!} = \frac{90}{256}$$

$$\text{and } P(\text{two identical strategies}) = 4.C_4^4.\frac{5!}{2!} + 3.C_4^3\frac{5!}{2!2!} = \frac{150}{256}$$

The fictive population is composed of 256 members; among these 256 members, only one has an ISF of 4, 15 members have an ISF of 3, 90 members have an ISF of 2 and 150 members have an ISF of 1. One-way analysis of variance (ANOVA) was used to compare observed ISFs with ISFs of the fictive population. A probability of less than 0.05 was required for significance.

Fig. 1 illustrates the kinematic parameters of one representative straightening up movement for one subject. The 'as fast as possible' instruction was well respected by all subjects. For all subjects and movements, the peak angular

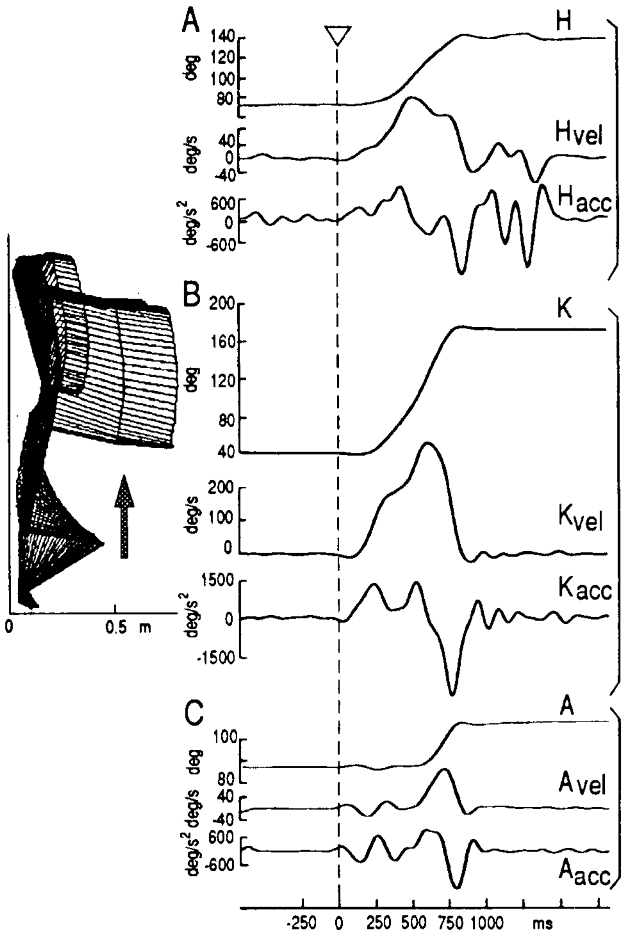

Fig. 1. Kinematic and kinetic analysis of the straightening up movement in one representative subject. Global movement sequence is represented in the kinogram (left). (A) Angular value (H), velocity (H_{vel}) and acceleration (H_{acc}) of the hip. (B) Angular value (K), velocity (K_{vel}) and acceleration (K_{acc}) of the knee. (C) Angular value (A), velocity (A_{vel}) and acceleration (A_{acc}) of the ankle.

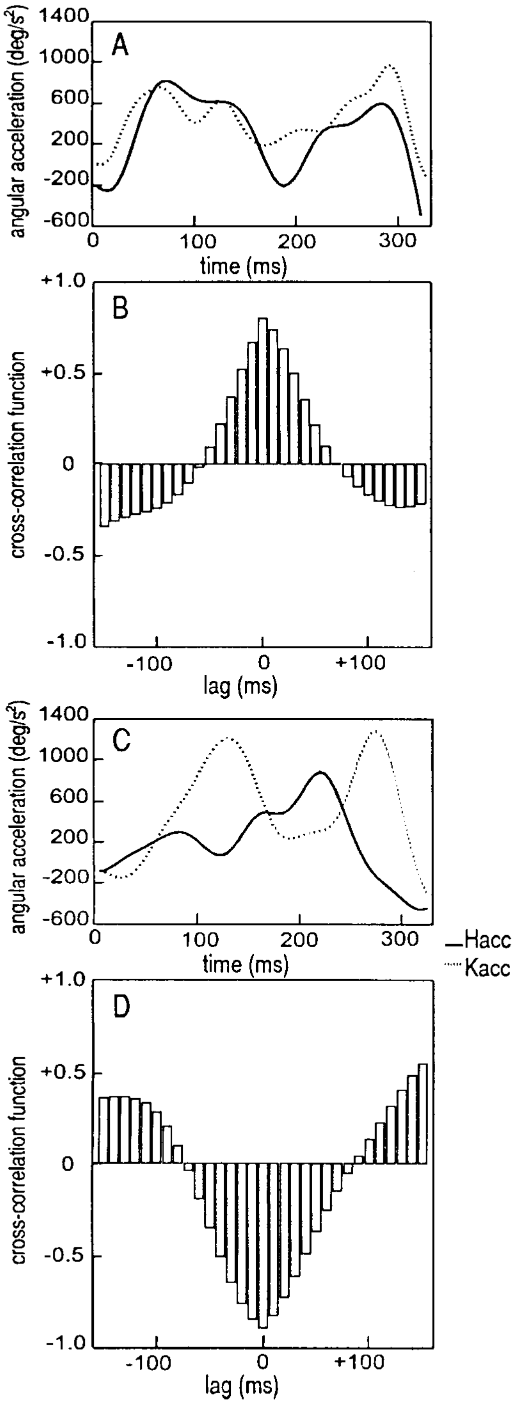

Fig. 2. Conjugate cross-correlation function (CCF) between hip (H_{acc}) and knee (K_{acc}) angular accelerations for two subjects showing the in-phase (A,B) and the out-of-phase (C,D) strategies. (A,C) Superimposition of the H_{acc} and K_{acc} traces analysed by CCF. (B,D) CCF histogram of the conjugate acceleration traces illustrated in (A) and (C), respectively.

velocity of the knee ranged from 316.7 to 432.0°/s (mean ± SD 392.6 ± 35.5°/s). The angular velocity profiles of the hip (H_{vel}) knee (K_{vel}) and ankle (A_{vel}) showed a consistent asymmetrical pattern in all movements and in all subjects. For example, in the illustrated subject the ascending phase of H_{vel} showed three sub-components corresponding to different acceleration pulses (Fig. 1A). The ascending phase of K_{vel} comprised two sub-components. For all subjects and movements, the duration of this phase ranged from 405 to 652 ms (mean ± SD 468 ± 82 ms). The first inflection corresponded to a transitory deceleration as evidenced in K_{acc} trace (Fig. 1B). The ankle velocity pattern was characterised by multiple peaks reflecting acceleration changes (Fig. 1C).

Fig. 2 shows the cross-correlation analysis between the hip and knee angular accelerations for two subjects. Fig. 2A,C show the superimposition of the H and K traces which were analysed by CCF as illustrated in Fig. 2B,D, respectively. This analysis clearly demonstrates a high positive CCF_{max} at a lag of 0 ms for the first subject (Fig. 2A,B), while the second subject presented a high negative CCF_{max} at 0 ms (Fig. 2C,D). The mean ± SD absolute value of the CCF_{max} was 0.64 ± 0.16 (calculated for a total number of 70 movements). The bimodal distribution of the CCF_{max} in positive and negative values enables one to define two distinct strategies, the in-phase and the out-of-phase strategy for each pair of joints (Fig. 3A–C). The categorization of the strategies in two opposite sets remains consistent with the fact that, within each of them, several temporal combinations can coexist. For example, a large positive value at a lag of +80 ms or −80 ms implies different relations between both waveforms yet they are members of the same IN or OUT strategy. The analysis of lag distribution for the three pairs of joints shows synchronisation around 0 ms (−20–+20 ms) for the H-K pair (Fig. 3E), and no consistent synchronisation for the other two pairs (Fig. 3D,F). Conservation of the type of strategy was evident in 10 subjects for H-K and K-A and in four subjects for H-A. Reproducibility of a combination of strategies for two pairs of joints was calculated with the ANOVA analysis of the real population ISFs versus the random population ISFs: the result was highly significant for HK-KA ($P < 0.0001$), significant

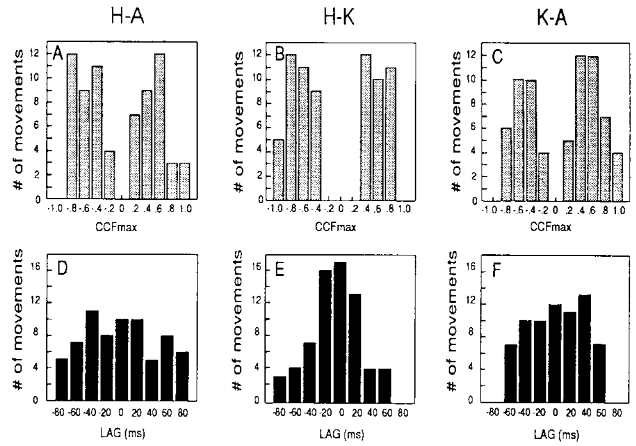

Fig. 3. Histograms of the maximal values of the cross-correlation function (CCF_{max}) (A–C) and of the corresponding lag values (D–F) for the hip-ankle (H-A), kip-knee (H-K) and knee-ankle (K-A), respectively.

for HK-HA ($P < 0.0027$), and not significant for HA-KA. Such significant values of the confidence degree prove that the coordination strategies are not chosen randomly.

In this study, we have focused our attention on the analysis of acceleration curves, because a large component of this parameter is proportional to the inertial load involved in the production of the initial rotation at each joint [14]. We found multiple acceleration and deceleration peaks for the three main joints of the lower limb during the early extension phase. These reflect extension and flexion net joint moments, while continuing extension of each joint is realised. A similar divergent solution between net joint moments and change in joint position have previously been observed in multi-joint movements where the distal segment exerts a force against the environment [15,16]. They are thought to be necessary for the realisation of a translation of a distal segment or the body centre of gravity through joint rotations [15,16].

Functionally, the emergence of two opposite coordination strategies means that the subcomponents of the angular acceleration occur simultaneously in the same direction or in opposite directions. These two coordination strategies may represent two different types of regulation of the distribution of the net torques over the hip and knee joints. A same divergent solution in kinematics profiles of the hip and knee was also recently demonstrated in locomotion [4]. In the latter study, two opposite groups of angular curves were recorded at the hip level in different subjects (see Fig. 6 in [4]) while the knee angular variation remained consistent across subjects. This pattern could correspond to opposite coordination strategies during a given epoch of the gait cycle in a similar way as that we found in the present movement. The fact that the statistical analysis of the ISF demonstrates a better reproducibility of the combination strategies for HK-KA than for the other two joint pair combinations (HK-HA and HA-KA) supports the existence of an organisational control of multijoint strategies of the lower-limb around the knee considered as the master central joint for the straightening up movement. Experimental evidences suggest that the biarticular muscles providing net torques transmission over the joints they cross play a central role in the coordination strategies. In different imposed strategies for sit-to-stand movement, the monoarticular muscles activation remains invariant while the biarticular muscles change their pattern significantly [6].

We thank Michelle Plasch for secretarial assistance. This work was supported by the Belgian National Fund for Scientific Research (F.N.R.S.), the Research Fund of the University of Brussels (U.L.B.) and the Banque Nationale de Belgique. B.D. is supported by the Fondation Van Goethem-Brichant and the Fondation Lekime-Ropsy. G.C. is also supported by the University of Mons-Hainaut, Belgium.

[1] Amblard, B., Assaiant, C., Lekhel, H. and Marchand, A., A statistical approach to sensorimotor strategies: conjugate cross-correlations, J. Motor Behav., 26 (1994) 103–112.
[2] Bernstein, NA., The Coordination and Regulation of Movement, Pergamon, Oxford, 1967, pp. 127.
[3] Bobbert, M.F. and Van Ingen Schenau, G.J., Coordination in vertical jumping, J. Biomech., 21 (1988) 241–262.
[4] Borghese, N.A., Bianchi, L. and Lacquaniti, F., Kinematic determinants of human locomotion, J. Physiol., 494.3 (1996) 863–879.
[5] Cheron, G., Bengoetxea, A., Pozzo, T., Bourgeois, M. and Draye, J.P., Evidence of a preprogrammed deactivation of the hamstrings muscles for triggering rapid changes of posture in humans, Electroenceph. clin. Neurophysiol., 105 (1997) 58–71.
[6] Doorenbosch, C.A.M., Harlaar, J., Roebroeck, M.E. and Lankhorst, G.J., Two strategies of transferring from sit-to-stand: the activation of monoarticular and biarticular muscles, J. Biomech., 27 (11) (1994) 1299–1307.
[7] Ferrigno, G. and Pedotti, A., Elite: a digital dedicated hardware system for movement analysis via real time TV-signal processing, IEEE Trans. Biomed. Eng., 32 (1985) 46–62.
[8] Horak, F.B., Nashner, L.M. and Diener, H.C., Postural strategies associated with somatosensory and vestibular loss, Exp. Brain Res., 82 (1990) 167–177.
[9] Jacobs, R., Bobbert, M.F. and Van Ingen Schenau, G.J., Mechanical output from individual muscles during explosive leg extension: the role of biarticular muscles, J. Biomech., 29 (4) (1996) 513–523.
[10] Keshner, E.A. and Allum, J.H.J., Muscle activation patterns coordinating postural stability from head to foot. In J.M. Winters and S.L. Woo (Eds)., Multiple Muscles System, Biomechanics and Movement, Springer-Verlag, New York, 1990, pp. 481–497.
[11] Nashner, L.M., Fixed patterns of rapid postural responses among leg muscles during stance, Exp. Brain Res., 30 (1977) 13–24.
[12] Pedotti, A., A study of motor coordination and neuromuscular activities in human locomotion, Biol. Cybern., 26 (1977) 55–62.
[13] Pedotti, A. and Crenna, P., Individual strategies of muscle recruitment in complex natural movements. In J.M. Winters and S.L. Woo (Eds.), Multiple Muscles System. Biomechanics and Movement, Springer-Verlag, New York, 1990, pp. 542–549.
[14] Stein, R.B., Cody, W.J. and Capaday, C., The trajectory of human wrist movements, J. Neurophysiol., 59 (6) (1988) 1814–1830.
[15] Van Ingen Schenau, G.J., Boots, P.J.M., de Groot, G., Snackers, R.J. and Van Woensel, W.L.M., The constrained control of force and position in multijoint movements, Neuroscience, 46 (1992) 197–207.
[16] Van Soest, A.J., Schwab, A.L., Bobbert, M.F. and Van Ingen Schenau, G.J., The influence of the biarticularity of the gastrocnemius muscle on vertical-jumping achievement, J. Biomech., 26 (1) (1993) 1–8.