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Muscle Synergies at the Elbow in Static and Oscillating Isometric Torque Tasks With Dual Degrees of Freedom

Gertjan J.C. Ettema, Emma Taylor,
J. David North, and Vaughan Kippers

This study's aim was to identify the effect of oscillation of torques in isometric tasks under identical mechanical conditions on the muscle synergies used. It was hypothesized that bi-functional muscles would play a lesser role in torque oscillation, because they would also generate an undesired oscillation. Thus, changes in muscle synergies were expected as a consequence of oscillation in torque generation. The effect of the trajectory of torque generation was investigated in dual-degrees-of-freedom submaximal isometric oscillation torque tasks at the elbow. The torques were flexion-extension and supination-pronation. Oscillation torques were compared with static torque generations at four torque positions during oscillation. Muscle activity was determined with surface electromyography. Compared with the static torque tasks, the oscillation tasks showed an overall increased muscle activity. The oscillation tasks, however, showed similar activity patterns and muscle synergies compared to the static composite tasks. It was found that the motor system is well able to control different orthogonal combinations of slow torque oscillations and constant torques by employing a single oscillating muscle synergy.

Key Words: musculoskeletal system, motor skills

Many studies have been performed within the theorem of the redundancy of degrees of freedom (df) of the motor system (Bernstein, 1967) yielding multiple (and, in principle, an indefinite) number of possibilities for the generation of one particular motor action. Still, a rather uniform muscle activity pattern is usually found among and within participants when performing a particular motor task (e.g., Buchanan, Moniz, Dewald, & Rymer, 1993; Cnockaert, Lensel, & Pertuzon, 1975; van Bolhuis & Gielen, 1997; van Bolhuis, Gielen, & van Ingen Schenau, 1998). It is thought

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that a larger number of underlying constraints, which could originate from the task or organism, are able to reduce the redundancy of degrees of freedom such that a controllable structure arises. In many studies, motor task constraints comprised movement velocity, force versus movement control, and joint configuration (e.g., Gottlieb, Chen, & Corcos, 1995; Lloyd & Buchanan, 2001; Theeuwes, Gielen, & Miller, 1994; van Bolhuis et al., 1998; van Bolhuis, Medendorp, & Gielen, 1997). One of the confounding problems in identifying underlying constraints is that several mechanical and physiological states (e.g., muscle length, velocity, joint torques) are altered when comparing the effect of the above-mentioned task variables. Thus, it is difficult to isolate the variables that determine the chosen coordination strategy from other altered variables.

Hunter, Ryan, Ortega, and Enoka (2002) found different fatiguing effects in a force task and a position task with identical mechanical constraints (isometric position task versus load task with identical position and load). These differences were attributed to differences in muscle activation patterns during the mechanically similar tasks. Thus, other than mechanical demands also affect muscle activity patterns. In the present study, we investigated to what extent time history of force direction determines muscle activity patterns, particularly in bi-functional muscles. In a complex multi-muscular system of agonists, antagonists, and synergists (elbow), alternating force tasks could generate an extra challenge for coordination. For example, when generating supination-flexion forces at the elbow, the biceps brachii might act as agonist. When generating pure supination force, the triceps brachii could act as synergist (nullifying flexion forces). In pronation and flexion, despite the flexion component, a reduced biceps activity is expected because of its strong contribution to supination. When alternating between these three force directions (changing from pronation-flexion, via pure flexion, to supination-flexion and vice versa), it is uncertain if the same muscle activity pattern as in the "static" tasks will be chosen: alternating biceps activity would result in desired alternating pronation-supination torques, but also in undesired fluctuations in the flexion torque. These could be counteracted by alternating triceps activity, but that strategy imposes an extra coordination demand in the execution of the task. Thus, on the notion that the most simple control strategy is preferred, we hypothesized that in the condition of torque oscillation, especially the bi-functional muscles would show a minimized or reduced oscillation in their activity pattern. On the other hand, if it was found that static and dynamic force tasks are accomplished by the same coordination strategy, this would support the notion that the combination of forces and torques generated by the participant is the main underlying factor in coordination of muscle synergies, despite the increasing complexity of control that could arise from this strategy.

We studied these effects of the trajectory of force direction in isometric force tasks at the elbow. The elbow was chosen as the model because it comprises a system of complex synergies in a dual-df system of flexion-extension and supination-pronation. The timing and trajectory constraint was a sinusoidal oscillating torque generation together with a constant torque generation in the orthogonal direction of that oscillation. The oscillation and constant torque were to be produced in various directions (see the following section for details). It was expected that the oscillation

constraint would cause partial inhibition of bi-functional muscles that would cause torque oscillation in the orthogonal direction as well. The experiments were designed such that mechanical and physiological task constraints were identical (or unlikely to be influential) between the task conditions that were compared.

Materials and Methods

Participants

Eight right-handed females ranging in age from 18 to 25 (mean age, 21.92 ± 0.97 years; height, 1.64 ± 0.08 m; weight, 60.63 ± 8.44 kg) participated in this study. The experiments were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki: ethical approval was obtained from the Medical Research Ethics Committee of the University of Queensland, and all participants were fully informed and gave their written consent.

Left-handed individuals were excluded because the equipment was designed for use by the right upper limb. Individuals with current or previous pathologies either at the elbow or the muscles acting across the elbow or any history of surgical procedures on the right upper limb were excluded.

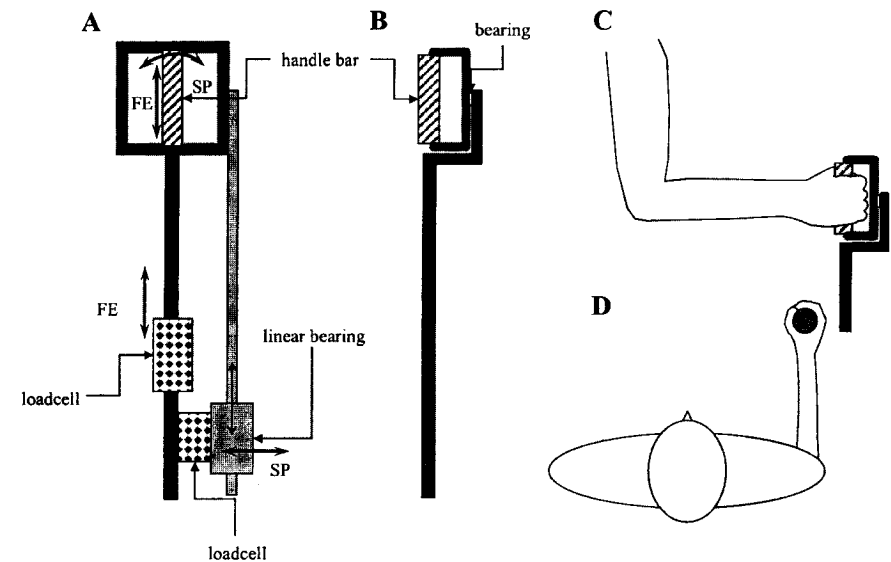


Figure 1—The isometric manipulandum, in frontal view (A) and from the side (B). The two bearings allow complete separate collection of two orthogonal forces, elbow flexion-extension (FE) and forearm supination-pronation (SP). Double-headed arrows indicate recorded forces. Position of hand and arm are shown from the side (C) and top (D).

Equipment

General Principles. The participants were seated in a chair with a specially designed manipulandum ("isometric joystick") installed for the right upper limb in a mid-prone forearm position (Figure 1A). The manipulandum was fitted with load cells (model V3SB, BLH Electronics, Canton, MA) to measure forces in both elbow flexion-extension (FE) and forearm supination-pronation (SP) directions. These forces, together with an electronically generated target, were displayed on an oscilloscope (Tektronix model 2215, 66 MHz), FE in vertical and SP in horizontal direction in accordance with the direction of torque generation and virtual movement on the manipulandum. With the participants seated and gripping the handle of the manipulandum, elbow angles were measured using a goniometer with an accuracy of 2°. The manipulandum was positioned so that each participant's arm was vertical with the forearm horizontal (measured elbow angle $91.25 \pm 4.43^\circ$). External lever arm sizes were required to calculate extension-flexion torques from the force recordings. The lever arms for each individual were measured between the olecranon and the handle of the manipulandum (0.276 ± 0.10 m). The olecranon was chosen as the bony landmark at the elbow because its position is relatively close to the center of rotation of the elbow joint (Veeger, Yu, An, & Rozendal, 1997). Rotational torques were derived from the manipulandum directly.

Manipulandum. Care was taken to prevent participants from using other degrees of freedom than elbow flexion-extension and forearm supination-pronation to generate the desired torques. During the execution of the tasks, the position of the elbow was controlled by a modest shallow restraint that did not prevent movement of the elbow but made the participant immediately aware that she was attempting an invalid action. In case of actual movement of the elbow out of the restraint, the trial was eliminated. This set-up made it impossible that torque actions in the shoulder (abduction-adduction) contributed to any of the torques of interest. Furthermore, as the forearm was in mid-prone position, wrist flexion-extension actions could not contribute to the measured flexion-extension torques. The manipulandum was tested for cross-transfer of other torques than the ones of interest: the only other action that would create a force on a load cell in measurement direction was sideways translation of the handle affecting supination-pronation torque measurements. To prevent this, the manipulandum was fixed in a quasi-stable manner: the participant did not need to keep it in place actively, but any significant torques other than the measured (and resisted) ones would lead to movement of the manipulandum. This situation specifically applies to internal-external rotation in the shoulder, wrist flexion-extension (both leading to sideways movement of the manipulandum), and shoulder flexion-extension (leading to forward-backward manipulandum movement). If any movement did occur the attempt was eliminated. After a short learning session, all participants were well able to maintain the manipulandum in one position. This allowed us to ascertain that in successful attempts the only net torques that were generated were the two torque directions of interest (with the possible exception of wrist deviation; see Discussion). No control was made for any joint fixation or stabilization strategies made by the participants.

Electromyography Recording. Preamplified bipolar surface EMG electrodes (QANTEC) were placed over six muscles: biceps brachii (BB), triceps brachii (TB), brachioradialis (BR), extensor carpi radialis longus (ECR_l), flexor carpi radialis (FCR), and pronator teres (PT). The EMG signals were band-pass filtered (10 Hz - 500 Hz) and amplified (QANTEC), and then recorded as computer files together with the force signals (model DI-200, DATAQ Instruments, Akron, OH, 12 bit A-D board, 1000 Hz sampling rate). The raw EMG data were full-wave rectified and integrated (IEMG), using a Butterworth low-pass filter with a 12 order, 5 Hz cut-off frequency. To match, in time, the EMG with the mechanical response it causes, an electromechanical delay value of 50 ms (Bober, Kornecki, Lehr, & Zawadzki, 1982; Komi & Cavanagh, 1977; Kornecki & Zschorlich, 1994) was used for time shift correction. Standard isometric maximal voluntary contractions (MVC) were performed to determine the 100% MVC EMG level. (BB, BR, elbow flexion at 90° mid-prone; TB elbow extension at 90° mid-prone; ECR_l wrist extension and FCR wrist flexion, both in preferred wrist position; PT forearm pronation from supinated position, elbow at 90°.)

Protocol

The main experiments comprised isometric contractions in a single joint position to ensure that all mechanical conditions were constant. To avoid the limits of the actuators' capacities (i.e., contraction rate, relaxation rate, and torque intensity) playing a controlling role, oscillating torque tasks at a low intensity (20% of maximum) and at low frequency (0.35 Hz) were employed.

Familiarization and Determination of Maximal Performance. The experiments were split in two separate sessions. In the first session the participants became familiarized with the equipment. The participants were seated on the chair holding the manipulandum in a mid-prone forearm position (arm pendant and elbow at 90°) with the oscilloscope (in X-Y mode) situated directly in front of the participant for real-time feedback of all contractions. Maximal voluntary contraction strengths (MVCS) were then determined. In all tests, the weight of the arm was removed from the total torque. Thus, in a completely relaxed condition, the torque was zero (at the origin on the oscilloscope). MVCSs were determined for flexion (F), extension (E), supination (S), and pronation (P). The efforts were maintained for approximately 2 to 3 s with at least 2 min rest between tasks to minimize muscle fatigue. The maximum torque of each MVC (being F: 34.26 ± 8.62 Nm; E: -30.59 ± 8.69 Nm; S: 6.07 ± 3.29 Nm; P: -4.74 ± 2.01 Nm) was measured over a period of at least 500 ms. To generate a symmetrical 20% MVC torque target frame, the lowest MVCS in flexion-extension and in pronation-supination were taken as the 100% level (Figure 2A).

Main Experiment. In the second session, a total of 15 tasks were assigned in random order to each participant. A 2-min rest interval was given between each task to minimize muscle fatigue. Eight static torque tasks were performed (Figure 2B) where the participants produced a torque in FE or SP direction, or a combination, equivalent to the 20% MVCS target value that was displayed on the oscilloscope.

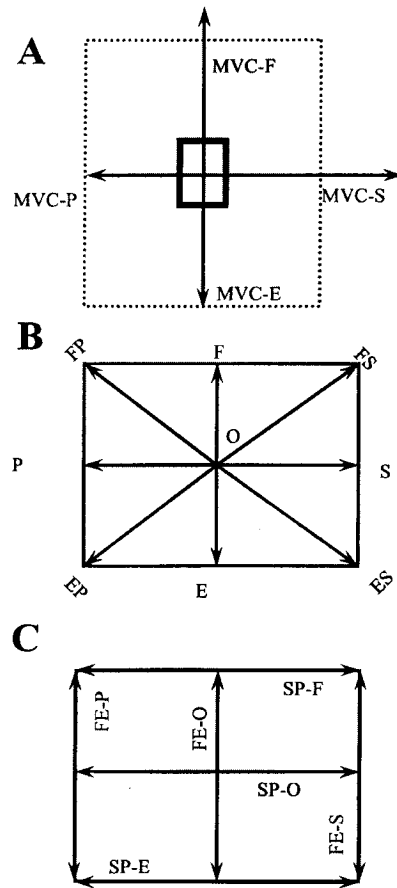


Figure 2—(A) Maximal voluntary contraction strengths (MVCs) for flexion (MVC-F), extension (MVC-E), supination (MVC-S), and pronation (MVC-P), indicated by arrows. The calculated 100% MVC (dotted square) and 20% MVC (solid square) targets are also shown. (B) Nine static task target positions (arrows) at the 20% MVC target. Target positions are FP, flexion-pronation; F, flexion; FS, flexion-supination; S, supination; ES, extension-supination; E, extension; EP, extension-pronation; and P, pronation. O denotes origin. (C) Six oscillation trajectory targets.

The torque was maintained for approximately 2 s. To simulate a 0.35 Hz frequency, this exercise was repeated three to four times in 10 s. Rests between each time were approximately 1 s. For the static tasks, EMG was averaged over a period between 100 and 200 ms, where a constant experimental torque (20% MVC) was generated. The torques and EMG were also recorded under fully relaxed conditions (torque at origin). The remaining six tasks were oscillation torque tasks, in which torque was alternated sinusoidally between two torque positions in either flexion-

extension or supination-pronation direction. The target torque was again set at the 20% MVCS level and oscillated at a frequency of 0.35 Hz. The target torque in the orthogonal direction was held constant, with or without an offset from the neutral torque (Figure 2C). Thus, the oscillation tasks could be grouped as FE-oscillations and SP-oscillations. Each group comprised two dual-df tasks (with constant offset) and one single-df task (no offset in orthogonal torque). The tasks were labeled according to the oscillation direction (FE or SP) and constant offset (F, E, P, S, O; O is origin, i.e., neutral torque). Three full cycles of these oscillation tasks were recorded while the participants continuously performed the task.

Data Analysis. In each cycle of an oscillation task, four torque positions, which corresponded with static torque tasks, were analyzed. The values of three cycles were averaged. The four torque positions consisted of the two end torque positions of the oscillation and two values passing through the center of oscillation (i.e., neutral torque or single degree of freedom torque positions of the oscillation). These torque positions are indicated by the torque combination generated. Thus, in the analysis, each oscillation task essentially consisted of, and was compared with, three of the static tasks.

Statistical Analysis

To ensure that conclusions drawn from differences between EMG data of the static and oscillation tasks were not the result of different magnitudes of torque production, the torque magnitudes for the static and oscillation tasks were compared using a two-tailed paired *t*-test for all four torque positions per task.

Two-way analysis of variance (ANOVA) tests for repeated measures on IEMG and torque data for the six oscillation tasks and their respective static comparison tasks were performed. F statistics from the ANOVAs were used to find any significance in the main effects (torque position and task condition) and interactions.

Results

Figures 3A and 3B show the activity levels and patterns for the six oscillation tasks and composite static tasks. Most muscles show an activity pattern consistent with the mechanical actions described by Ettema, Styles, and Kippers (1998). A few direct observations can, however, be made relating to synergistic actions. The triceps brachii shows highest activity during extension with supination, most likely acting as a synergist/antagonist for the biceps brachii. The biceps brachii is active during tasks involving flexion or supination. It seems less active, however, during a flexion-pronation task, which might indicate its strong action in supination (Ettema et al., 1998). The brachioradialis and extensor carpi radialis longus do not show an activity pattern consistent with their elbow flexion action, except for its low activity in pure flexion. The flexor carpi radialis shows pronation activity that is in agreement with Ettema et al. (1998).

All oscillation tasks and their respective composite static tasks were compared to determine a potential difference between torque values in the static and oscillation tasks in any of the degrees of freedom (Table 1). In five cases, a significant difference was found, three of which correspond to an enhanced overall muscle

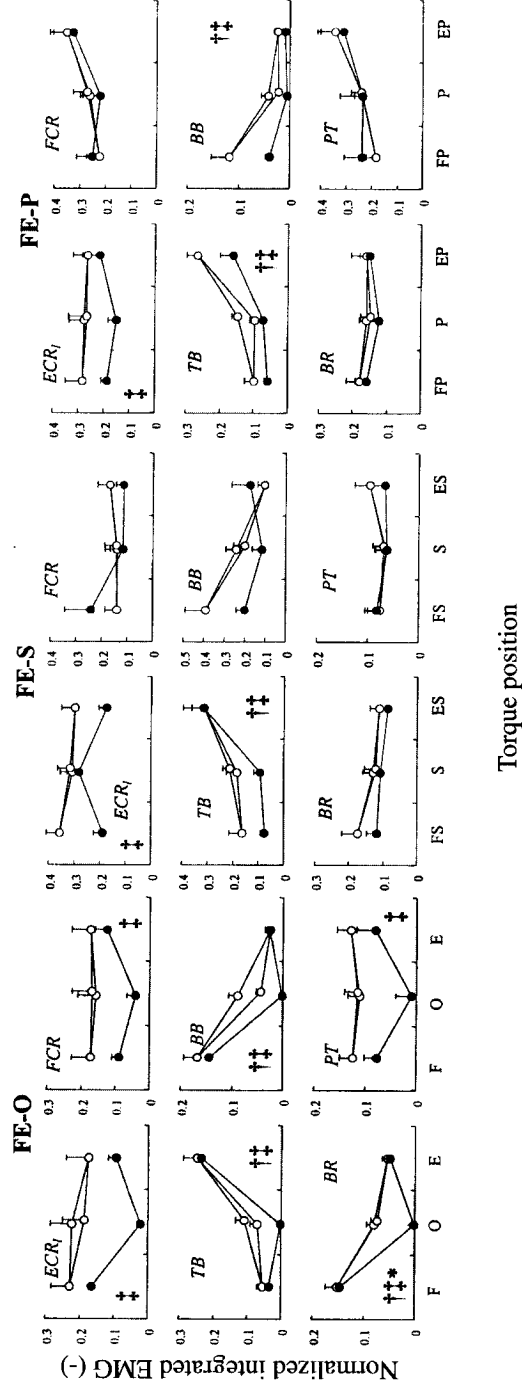


Figure 3A — Normalized integrated EMG (%MVC) (mean and SEM, $n = 8$) for the six FE oscillation tasks (open circle) and composite static tasks (solid circle) at 4 positions during the oscillation cycle. In case of hysteresis, curved arrows indicate the direction of the activity cycle. Significant torque effect (*), task effect (†), and interaction effect between task and torque position (*) are indicated.

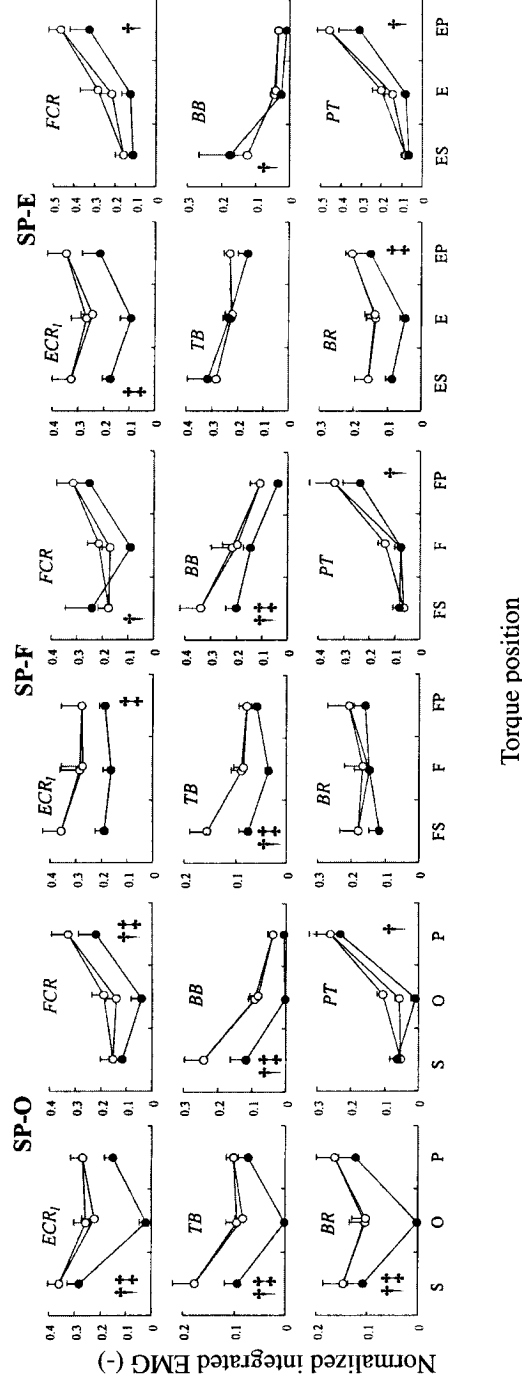


Figure 3B — Normalized integrated EMG (%MVC) (mean and SEM, $n = 8$) for the six SP oscillation tasks (open circle) and composite static tasks (solid circle) at 4 positions during the oscillation cycle. In case of hysteresis, curved arrows indicate the direction of the activity cycle. Significant torque effect (*), task effect (†), and interaction effect between task and torque position (*) are indicated.

Table 1 Torque Differences (in Fraction of Target Values) Between Oscillation and Composite Static Tasks

Torque	Oscillation Task*											
	FE	SP	SP-F	FE-S	SP-E	FE-P						
SP(x)	F	0.11	S	0.35*†	FS	0.14	FS	-0.02	ES	0.14	FP	-0.02
FE(y)		0.15		0.14		0.10*		0.15		0.22*†		0.14
SP(x)	O	-0.03	O	—	F	—	S	-0.42*	E	—	P	0.12
FE(y)		—		0.03		-0.00		—		0.15*†		—
SP(x)	E	-0.04	P	-0.06	FP	-0.23	ES	0.00	EP	0.04	EP	-0.07
FE(y)		-0.11		0.02		0.01		-0.07		-0.01		-0.07

*Statistical significance ($p < .05$). †Indicates that the difference is in agreement with (and might explain) the overall difference in muscle activity between oscillation and static tasks (Figures 3A and 3B). The symbols in the table indicate the force locations of comparison.

activity level (see Figures 3A and 3B and the section "Static Versus Oscillation Task"). The analysis presented below includes all data and does not account for these torque differences. The exclusion of these cases led to minor differences in the results and did not affect the major conclusions drawn.

In Figures 3A and 3B, the ANOVA results for IEMG values of six muscles as a function of task and torque are indicated. The interpretation of these statistics is as follows: A significant effect of "task" indicates a difference in mean activity level between oscillation and composite static tasks. A "torque" effect indicates a change in activity during an oscillation task or among the composite static tasks. These muscles can be considered to be, directly or indirectly, involved in generating an alternating torque. A significant interaction indicates that the activity patterns differ between the oscillation and static task condition.

Static Versus Oscillation Task

The oscillation tasks usually showed a higher muscle activation level, which is statistically significant in 21 out of 36 occasions. This activity enhancement is not merely restricted to the origin torque position in the single-df tasks (FE-O and SP-O) which could be easily explained as follows: at the origin, the static task consisted of maintaining zero torque, leading to a low muscle activation level, whereas in oscillating tasks the participant is transferring to opposite torques, which requires muscle activity. In addition, during the dual-df oscillation torque tasks (with offset torque), an enhanced activity level was often found. In three cases, the activity enhancement could have resulted in elevated torque levels during the oscillation tasks (see Table 1).

Torque Effect

From Figures 3A and 3B it was deduced that in all oscillation tasks a synergistic group of muscles generated the required torque oscillation combined with a constant torque in the orthogonal direction.

Flexion-Extension Oscillation. During the FE-O task, the TB, BB, and BR seem to generate the flexion-extension oscillation, whereas FCR and PT might act as synergists to nullify the supination oscillation caused by the alternating activity of BB. In the FE-S and FE-P tasks, the TB and BB also seem to be the main muscles generating the torque oscillation. The BR, however, is not involved in this manner. For these two tasks it is not obvious from the results which muscle acts as synergist to produce a constant torque in the supination-pronation direction.

Supination-Pronation Oscillation. In all three SP oscillation tasks, BB, PT, and FCR generate the supination-pronation oscillation, and TB counteracts the flexion oscillation generated by particularly BB. The ECR₁ and BR only occasionally show alternating activity.

Overall, at the elbow, the TB and BB (and, to a lesser extent, the PT) seem to be the dominant muscles with regard to creating the particular force directions (significant torque effect at all tasks).

Interaction Effect

One out of 36 muscle-task combinations showed a significant interaction effect (Figures 3A and 3B), i.e., a different alteration in activation between torque positions in oscillation and static tasks was found for the BR in the FE-O task. This interaction can be attributed to the enhanced activity in the neutral position in the oscillation condition. Only in one other nonsignificant case, there seems to be a clear difference in the basic activation pattern (BB in FE-S). Generally, if an alternating activity pattern is apparent for a static task condition, this pattern also occurred during the oscillation condition.

Discussion

The major aim of the study was to investigate the effect of torque history on coordination patterns during isometric dual-df torque tasks at the elbow. For that purpose, torque oscillation tasks were compared with static torque generation at four positions during the cycle. The activity patterns during static torque generation were considered as the control without any additional task constraints. Six muscles were studied using surface EMG. Thus, the results can only be interpreted at the level of synergies among muscles, not among subpopulations of motor units (e.g., Caldwell, Jamison, & Lee, 1993; van Zuylen, Gielen, & Denier van der Gon, 1988). A number of consistent synergies were identified. The BB and TB seem to be the main muscles generating the flexion-extension oscillation, whereas the BR is much less involved. In supination-pronation oscillations, the BB, PT, and FCR appear to generate the torque oscillation and the TB acts as the main synergist to nullify FE oscillations. These synergies are hardly affected by task constraints (static versus

oscillating tasks), which contradicts the findings of Buchanan, Rovai, and Rymer (1989) and Buchanan and Shreeve (1996), who did not find such fixed synergies. This could be because in this study a single joint configuration (midrange of movement) was examined, leaving mechanical actions of the muscles constant among different tasks.

Synergies in Oscillation Generation

Apart from enhanced (antagonistic) muscle activity, only in one of 36 occasions was a statistically significant difference in the intermuscular activation pattern between oscillation and static task conditions found. The difference between the conditions was torque history. Torque position, as well as overall frequency of torque development and relaxation, was the same. Furthermore, the task constraints were such that physiological and mechanical capacities of muscle were unlikely to be a limiting and therefore controlling parameter in the coordination of the task. Thus, the present findings indicate that the synergies are hardly affected by the history of task (timing and trajectory) as is the case with mechanical and physiological task constraints (e.g., Tax, Denier van der Gon, & Erkelens, 1990; Theeuwens et al., 1994; van Bolhuis & Gielen, 1997). Still, this modest influence of history constraints on activity patterns and significant effect on activity levels within a particular muscle synergy could explain why physiological and mechanical optimization approaches have limited success in predicting muscle activity patterns (e.g., Buchanan & Shreeve, 1996).

During the oscillation tasks a seemingly complex strategy is adapted to generate a torque oscillation in combination with a constant orthogonal torque. No attempt is made to abandon the use of dual-task muscles that generate orthogonal torques that are not involved in the oscillation pattern. Rather, the unintended oscillation is nullified by synchronous oscillation of synergistic muscles. The best example is the strong rhythmic activation pattern of the BB, a strong flexor and supinator, during all oscillation tasks (see also Figure 4). In SP tasks, the TB functions as synergist of the BB. In FE tasks, this function could have been performed by the pronator quadratus (not measured). As the torque tasks were performed at 20% MVCS, it seems unlikely that this strategy was adopted because of limited capacity of the muscle system or any of its subcomponents. For example, in the FE-S task, the TB could easily have generated the flexion-extension oscillation, with constant BB activity that would have generated the constant supination offset in combination with a flexion torque component.

Synergy Adjustments—Enhanced Muscle Antagonistic Contraction

During the oscillation tasks at the elbow, enhanced contraction was seen in most muscles when compared to the static tasks. This was observed not only at the neutral torque position, where the static task merely constituted “generating no torque at all.” The activity enhancement is consistent with the presumption that the oscillation tasks were more difficult to perform than the static tasks, which was reported by the participants. It seems reasonable to suggest that when the torque task is more difficult, an enhanced co-contraction occurs to allow better control of

the task by means of a stiffer system. Although the participants had familiarized themselves with the experimental tasks, these were relatively novel to them. Hence, this study cannot indicate if the synergies are optimal and remain unaltered during practice and learning.

Methodological Considerations: Cross-Talk

The present findings could have been affected by cross-talk of the EMG signals. In that case, the strength of the synergies identified in this study is exaggerated. The strongest synergistic functions, however, were identified for muscles that are clearly separated anatomically (BB and TB) where cross-talk is more a theoretical issue than a practical one. This is supported by the data presented in Figure 4: where the BB and TB EMG data are tightly coupled in the SP tasks (TB acting as synergist for BB), they are fully out of phase in the FE tasks (acting as antagonists). These results are incompatible with significant cross-talk. In addition, the PT tracings in Figure 4 are in agreement with its mechanical actions and thus incompatible with significant cross-talk from muscles with other mechanical effects. An analysis of cross-talk was not performed, as it is difficult to differentiate between a common component of two signals that is functional and originates from a synergistic action (muscle coactivation) and a common component that is caused by cross-over of electrical signals from two muscles to the reciprocal electrodes (cross-talk; Lowery, Stoykov, & Kuiken, 2003). Thus, with potential cross-talk in mind, the details for some individual muscles as BR, ECR₁, FCR, and PT should be considered with caution. In defense of the conclusions drawn, however, one could consider the EMG recordings representations of muscle compartments, divided on other than anatomical grounds. The findings would lead to the same conclusions, although the explanation of the activity patterns in terms of mechanical outcome then becomes somewhat more confused. Moreover, as mentioned above, the findings on the BB and TB (for which cross-talk is not a concern) best exemplify the rejection of the hypothesis tested. Thus, it seems unlikely that the major conclusion (i.e., arguing for one synergy, independent of task condition) is caused or affected by possible cross-talk on some muscles.

Methodological Considerations: Nonmonitored Degrees of Freedom and Quasi Degrees of Freedom

The present description at the intermuscular level is not complete as a number of important muscles, such as brachialis, supinator, and pronator quadratus were not considered. None of these, however, can be considered bifunctional (supinator has an estimated flexor strength of only 6% of BB; Ettema et al., 1998). Thus their unknown activity patterns would probably be relatively easy to interpret and, moreover, would not likely have a strong bearing on the interpretation of the current results.

The experiments were carefully designed to prevent participants from generating other torques than in the two degrees of freedom of interest. The only action not accounted for is radial and ulnar deviation in the wrist in generation of flexion-extension torques. In the set-up used, however, this wrist action is completely

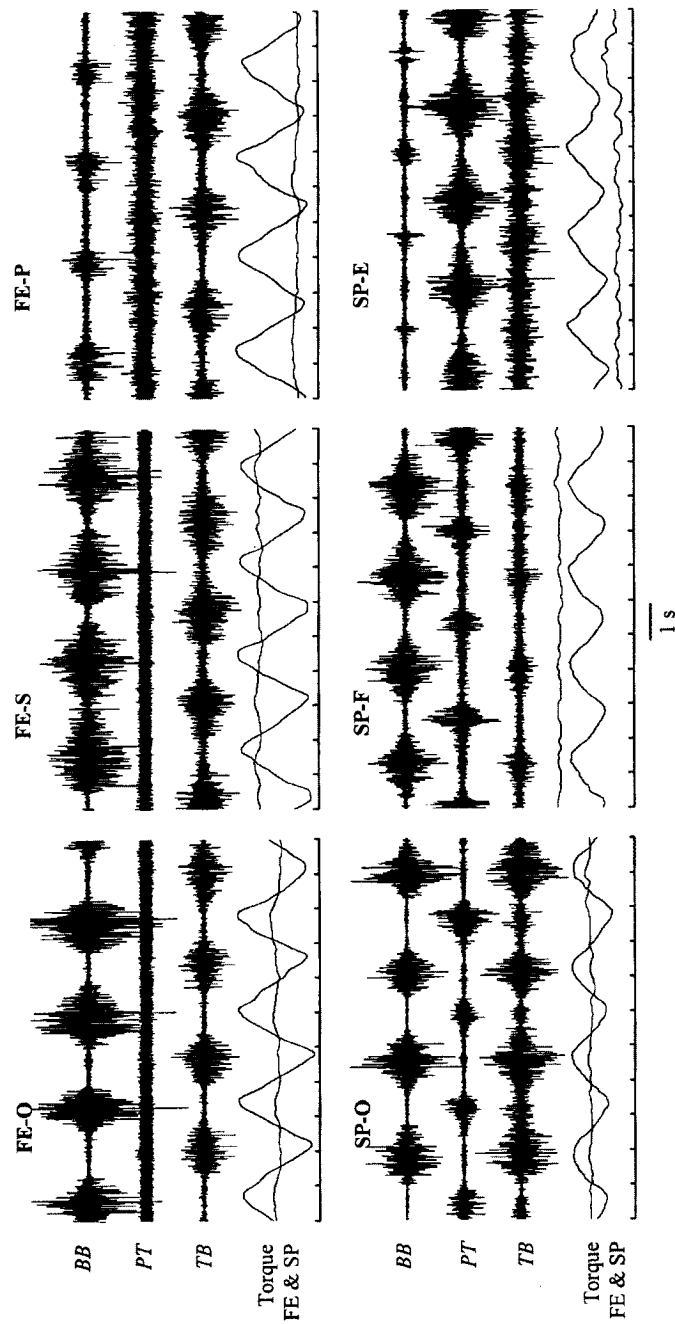


Figure 4—Examples of raw EMG of BB, PT, and TB during the six oscillation tasks at the elbow. During the FE oscillations (top diagrams) the BB and TB act as antagonists, and during SP oscillations (bottom diagrams) as synergists (only in the SP-E task, this synergy is almost completely obscured by the high continuous TB activity and minimal BB activity bursts). The PT shows a constant activity level in FE tasks and antagonistic oscillating behavior with the BB in SP tasks.

coupled to the torque generated at the elbow. For the flexion-extension action, these two joints are connected in series; to fulfill the requirements of equilibrium of moments and forces, the torques to be generated in both wrist and elbow are completely dependent on each other. Although one might think of generating a flexion-extension torque by two control strategies, i.e., “from the wrist” and “from the elbow,” and although these strategies could be perceived as different in terms of muscle activation, mechanically (i.e., net joint torques) there is no difference. The issue could have been avoided by connecting the manipulandum at the forearm. The results might have been different because relative wrist strength (or weakness) might have acted as a boundary condition for the available options in muscle activity patterns. It is beyond the scope of this article to further elucidate on this issue, but, depending on the particular task and situation, the redundancy of degrees of freedom could be smaller than estimated on the basis of the number of joints, movement directions, muscles, etc.

Effect of Nonboundary Conditions

This study was done under nonboundary conditions, i.e., well within the capacities of individual muscles (e.g., strength, activation-relaxation rates). It therefore also bears little direct relevance for practice (e.g., ergonomics, FES). It is not clear if the same comparison between static and oscillation conditions would have been found at higher loads and oscillation frequencies. Therefore, these results might not generalize to oscillatory actions at frequencies higher than employed here. The current study, however, has provided fundamental information about the choice in control strategy that could be employed under specific circumstances.

Conclusion

From the present results it seems that the motor system is capable of controlling different orthogonal combinations of torque oscillations and constant torques by employing a single oscillating muscle synergy. The use of one main strategy (but adaptable to constraints) seems to be preferred over utilizing two independent control mechanisms, one for the oscillation and one for the constant torque component.

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The Effect on the Use

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The uncontrolled manifold a space location on the use of n reaching. Participants pointe lateral workspaces at two dif workspace, the component o identical hand path across tr of joint configuration varian magnitude of this difference minimally by target distance ing ipsilaterally was associa compared to reaching contra affected by target orientation reasons that lead to the obser

Key Words: redundancy, reach

The performance of goal-directed different spatial locations (Barth Goodale, 1996; Carey & Otto-d 1990; Carson, Goodman, Chua Ghilardi, Cooper, & Ghez, 199 Kalaska, 1997). Specifically, re the hand (same side of the body shorter movement time, higher reaching to comparably placed t site side of the body midline). such a spatial asymmetry in per interhemispheric communicatio field contralateral to the reachin initially projected into the hemi sensory cortices having direct o

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