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The coupling between upper and lower extremity synergies during whole body reaching

T.R. Kaminski *

Department of Biobehavioral Sciences, Teachers College, Columbia University, Box 199, 525 West 120th Street, New York, NY 10027, USA

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Abstract

When performing whole body reaching movements, all four limbs participate in the task. We hypothesized that the synergies that characterize upper and lower extremity movement are flexible and become coupled into one functional unit to transport the body towards the target. To test this hypothesis, subjects reached to three targets, one within and two beyond arm's length. In addition, subjects reached at two speeds and either stopped at the target or returned to the original start position. To assess the coupling during the various whole body reaches, a principal component analysis was performed on the displacements of the five primary joints used to accomplish the task (ankle, knee, hip, shoulder and elbow). Analysis of the loadings from the principal component analysis indicated that the first component represented the reaching element of the task, while the second and third components represented the postural element. When reaching within arm's length the variance explained by the joint coupling was distributed between the first three principal components. However, as reach distance increased, the distribution shifted with most of the variance being explained by the first principal component. Neither movement velocity nor final joint configuration affected the coupling between the joints. Analysis of center of mass indicated that it shifted progressively forward as reached distance increased. We conclude that as target distance increased, the reach and postural synergies became coupled resulting in the arms, legs and trunk working together as one functional unit to move the whole body forward.
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1. Introduction

To simplify motor control, moving joints are frequently linked together to form functional synergies. For example, it is well established that the elbow and shoulder joints are linked together as a single unit when pointing or reaching [1,2]. When trunk motion is incorporated into a reach, it becomes coupled to that of the arm [3–6]. Similarly, the ankles, knees and hips become functionally coupled during trunk flexion and extension performed in a standing position [7,8] and during perturbations to the support surface [9–11] to minimize center of mass (CoM) displacement.

Several studies of simple arm movements performed from a standing position have led to the conclusion that postural and focal elements can be partitioned into two parallel, separately controlled processes [12–14]. During these types of movement, it has been suggested that the legs and trunk act together to stabilize the body from the effects of the interactional forces generated by the focal movement and minimize displacement of the CoM [12,15–18]. Recent research on whole body reaching blurs this dichotomous view of posture and movement and indicates that the legs and trunk play a dual role. Not only are they responsible for maintaining postural stability, but they also contribute to transporting the hand to the target [19–21].

We hypothesized that, depending on whether a target is within or beyond arm's length, the role of the lower extremities changes from a relatively autonomous movement unit providing postural stabilization to part of a larger unit that is coupled with the arm to move the body towards a target. To test this hypothesis, subjects reached to three

* Tel.: +1 212 678 3325; fax: +1 212 678 3322.
E-mail address: kamin4@optonline.net.

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targets, one within and two beyond arm's length. In addition, subjects reached at two speeds and ended the movement by either stopping at the target location or returning to the original body configuration. Changing the movement speed and distance affects the inertial and interactional forces associated with the movement and thereby alters the stability demands of the task.

To assess whether the task could be divided into somewhat separate postural and reach synergies, a principal component analysis (PCA) was performed on the primary joints used during the whole body reaches. This type of analysis can reduce a large set of interrelated variables (joint displacements) into a smaller number of components while maximizing the amount of variance that can be explained in the data. If movements can be separated into somewhat autonomous postural and focal synergies, the variance in joint motion should be distributed between two or more PCs. Furthermore, the regression coefficients for upper extremity joints should be high on one PC while coefficients for the lower extremity joints should be high on another PC. Alternatively, if motion of the five primary joints acts together as a unit, then most of the variance should be explained by one PC that has high regression coefficients for both upper and lower extremity joints. Finally, if the movement organization differed for reaches within and beyond arm's length, then different movement patterns and regression coefficients should be observed, depending on target distance.

2. Methods

2.1. Subjects

Six right-handed female subjects (32.4 ± 4.1 years) without neurologic or current orthopedic impairments were recruited for this study. The nature of the experimental conditions was explained to all subjects who then signed a written informed consent form. The form and study were approved by the IRB of Columbia University and were in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.2. Testing procedures

Subjects stood on a forceplate and performed three variations of bimanual whole body reaching to a plastic bottle (100 g in weight, 30 cm in height, 10 cm in diameter) positioned in the mid-frontal plane at the level of the anterior superior iliac spine. All reaches were performed with feet parallel, at a self-determined width apart, shoulders in 0° of abduction, elbows in 90° of flexion, and palms placed on the anterior superior iliac spines. Upon hearing the verbal instruction "go", reaching was initiated with both arms. In the first variation, subjects reached as fast as possible to the bottle without grasping it and stopped (stop/fast). In the two other variations subjects reached, grasped the bottle and returned it to the starting position at two speeds: as fast as possible (transport/fast) and at a self-paced speed (transport/slow). In addition, subjects performed these three reaching variations to three distances: close (100% arm's length, no trunk movement), middle and far (maximum reach with trunk, heels remaining on ground). The order of target presentation was randomized, with subjects performing 54 trials: six reaches at three distances per variation.

2.3. Instrumentation and data reduction

Reflective markers were placed along the right side of the body over the second metatarsal, lateral malleolus, femoral condyle, greater trochanter, lateral humeral epicondyle, ulnar styloid process, seventh cervical vertebrae, and earlobe. Trials were videotaped in 2-D at 60 Hz and digitized automatically using Peak Motus 6.1 data acquisition system (Englewood, CO), then low-passed filtered at 6 Hz using a Butterworth dual-pass digital filter.

2.4. Data analysis

Since all reaches were bilateral, movements were assumed to be symmetrical and required minimal trunk rotation. Sagittal whole body CoM was determined using a seven-segment, rigid body model derived from the reflective markers and consisted of the following segments: foot, shank, thigh, trunk, head, upper arm and forearm. Segmental body weights and CoM locations were estimated using formulas provided by Winter [22].

Ankle, knee, hip, shoulder and elbow joint angles were derived from the reflective markers. The start of movement was considered the point in time when angular velocity of any of these joints exceeded $2.5^\circ\,s^{-1}$. Similarly, end of movement was the time when the velocity of all joints fell below $2.5^\circ\,s^{-1}$.

Separate PCAs were performed on each subject's data to assess the effect of movement conditions on joint coupling. The five joint angles obtained from each time sample starting at onset of joint movement and ending with arrival at the target (wrist tangential velocity below 4 cm/s) were the basis for each PCA. Since there was a large disparity between angular displacements of the hip, shoulder and elbow compared to the ankle and knee, the correlation matrix was used as a means of standardizing the joint displacements and assured equal representations of all joints in the PCA. The basic PC postulate is: $z_j = a_{j1}\mathrm{PC1} + a_{j2}\mathrm{PC2} + \cdots + a_{ji}\mathrm{PC}_i + d_jU_j$ where z_j stands for displacement of joint j, U_j for unique factor for joint j, a_{ji} stands for standardized regression coefficient of j on i.

Summary measures were combined across the six subjects and used in repeated measures regression analyses. Forward stepwise regression was used to assess the effect of the conditions (target distance, fast versus slow, stop versus return) on each of dependent variables (displacement,

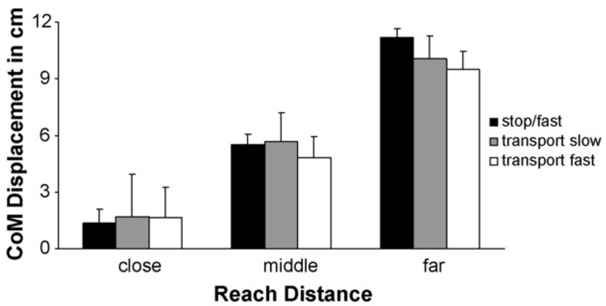

Fig. 1. Means and standard deviations of CoM displacements for the three distances and three movement variations. Note that shifted forward even for the closest target and increased proportionally with target distance.

movement onset, etc.). A condition was considered to have a substantial effect if the addition of that condition to the regression equation significantly increased ($p < .05$) the amount of explained variance. Orthogonal contrasts were used to determine which target distances had a unique effect.

3. Results

3.1. Center of mass and joint displacements

CoM displacement consistently shifted forward towards the target (see Fig. 1), even when the task could be completed without trunk motion. Furthermore, displacement at all joints increased as reach distance increased (see Fig. 2). Displacements were not affected by reach speed or final body configuration as the amount of variance explained did not change by the addition of these variables to the regression equation.

3.2. Timing of joint movement

When reaching to the close target, movement began with shoulder flexion, followed by hip, ankle and knee motion (see Fig. 3). In contrast, when reaching to the two farther targets, motion was initiated at the hip, followed by knee, ankle and shoulder. Orthogonal contrasts indicated a significant difference in the onsets of the ankle, knee and hip relative to the shoulder for reaches to the close target compared with reaches to the two farther targets

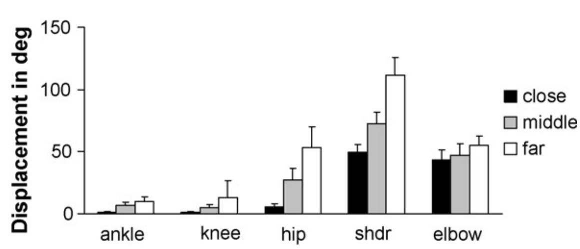

Fig. 2. Means and standard deviations of joint displacements averaged across movement speed and final joint configuration. Knee joint displacement is based upon absolute displacement.

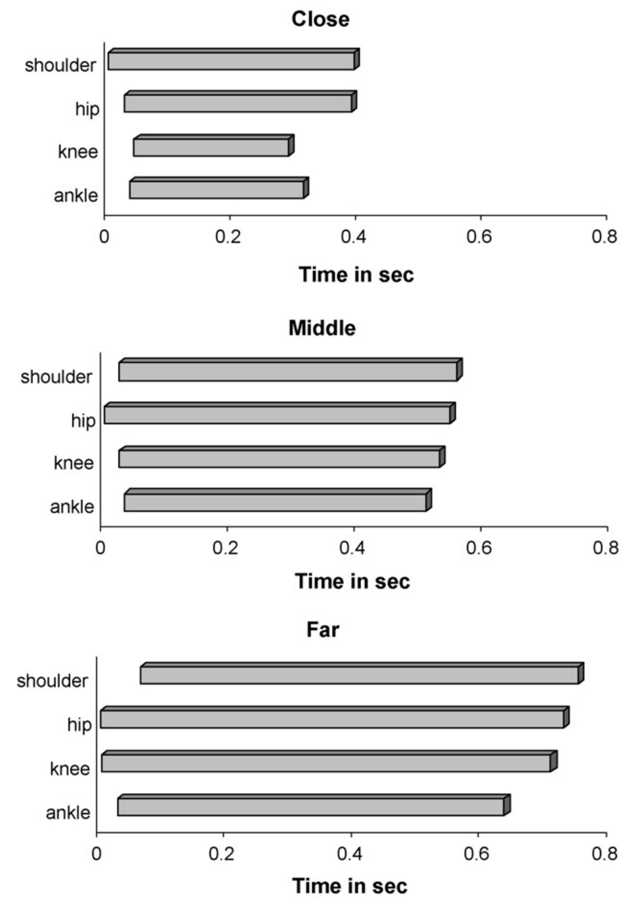

Fig. 3. Floating bar graphs representing means for total movement time, timing of joint movement onset and termination averaged across movement speed and final configuration. Timing relationships differed for the close compared to middle and far targets, but movement termination was not affected by any of the conditions.

($F_{5,38} = 4.62$, 6.81 and 4.00, $p < 0.01$ for the ankle, knee and hip, respectively). Thus, joint coordination differed depending on whether trunk and legs were required to participate in the reach. Task conditions had no effect on the timing relationships between the joints.

Regression analysis indicated no differences across conditions as to when joints stopped moving. The ankle joint completed its motion towards the target first, while the knee and hip stopping moving simultaneously or slightly before the shoulder joint (see Fig. 3).

3.3. Principal component analysis

More than 98% of the variance in the displacements of the five joints was accounted for by the first three PCs. Consequently, the findings related to PC4 and PC5 were not included in the results. The distribution of variance differed for reaches to the close compared to the middle and far targets (Fig. 4A). Orthogonal contrasts from regression analysis indicated that the amount of variance explained by PC1 was significantly different for reaches to the close (53%) compared to the middle (81%) and far (87%) targets

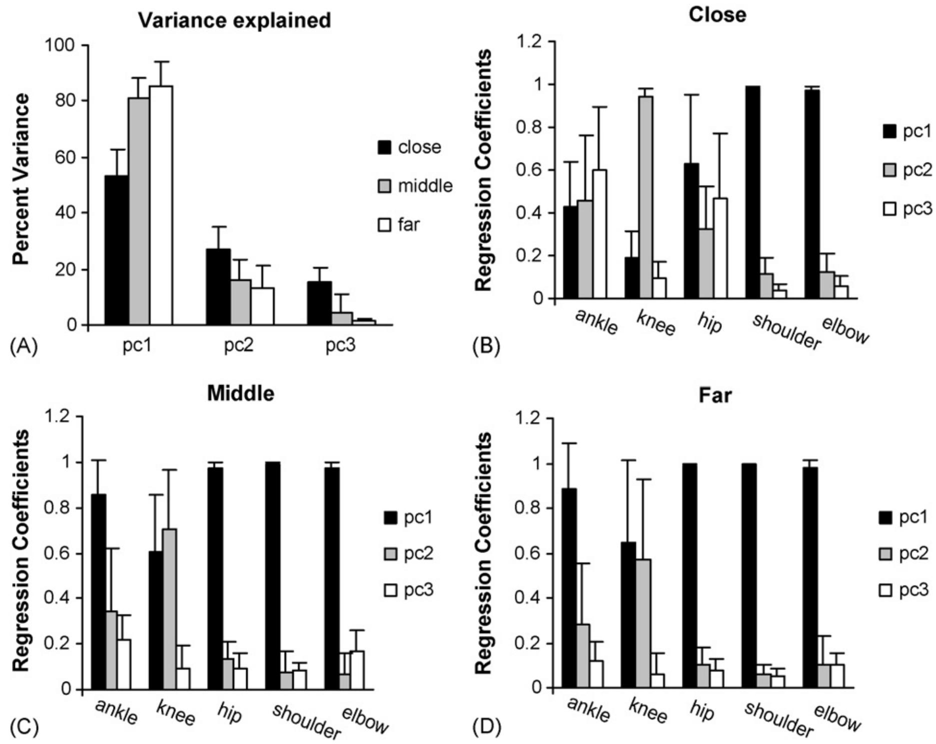

Fig. 4. (A) Means and standard deviations of the percentage of variance explained by the first three principle components for the three target distances, averaged across subjects. (B–D) Means and standard deviations of the regression coefficients on the first three principle components at each target distance, averaged across subjects.

($F_{5,38}$ = 7.04 and 26.20, $p < .001$, respectively). Thus, the joint regression coefficients associated with PC1 provided a very strong representation of the relationship between the joints when reaching beyond arm's length. When reaching to the close target, the high amounts of variance explained by PC2 and PC3 indicated that these different coefficient patterns offered viable joint coupling alternatives.

Fig. 4B–D show the regression coefficients for each of the five joints at each target distance. The high shoulder and elbow coefficients in PC1 indicated that these joints were strongly coupled at all distances and represented the reach synergy. The pattern of regression coefficients for the lower extremity joints was markedly different. These coefficients were much smaller on PC1 when reaching to the close target, indicating that their coupling to arm motion was loose. In PC2 and PC3, the lower extremity coefficients were larger, with hip and ankle motion being coupled (PC3), and the knee moving independently (PC2). When reaching beyond arm's length, the lower extremity coefficients on PC1 increased dramatically, signifying that these joints became more tightly linked with arm motion. The high regression coefficients for the ankle and knee in PC2, combined with the fact that it explained 16% of the variance indicated that these joints moved together, but were not completely synchronized with upper extremity movement. This pattern of lower extremity motion was more likely related to the postural adjustments that were made to maintain stability. Note that for reaches to the middle and far targets the hip coefficients were large on PC1 and small on PC2 and PC3. Thus, hip displacement was more tightly coupled to motion of the arm than to that of the leg when reaching beyond arm's length.

Angle–angle plots were used to clarify some of the findings of the PCA. The angle–angle plots depicted in Fig. 5 are ensemble averages of one representative subject and illustrate the coupling across the three movement conditions and three distances for various pairs of joints (reach phase only). The critical features of these plots are the dispersion and slopes. A narrow dispersion and similar slopes indicate that the same coupling was present between a pair of joints across movement conditions. Furthermore, the coupling *within* the upper or lower extremity (Fig. 5A and C) was just as strong as that observed *between* the upper and lower extremities (Fig. 5B).

In contrast, distinct differences can be observed in the plots when comparing reaches that were within and beyond arm's length. As illustrated in Fig. 5A, the relationship between shoulder and elbow displacement changed depending on trunk involvement. When reaching to the close target, there was much less shoulder motion and a steeper slope than when reaching to the middle and far targets. This distinction between reaches that were within and beyond arm's length can also be seen in the hip–ankle plot (Fig. 5C). Although displacements were relatively small when reaching to the close target, the slope was much steeper than that observed for reaches to the two farther targets. Similarly, the

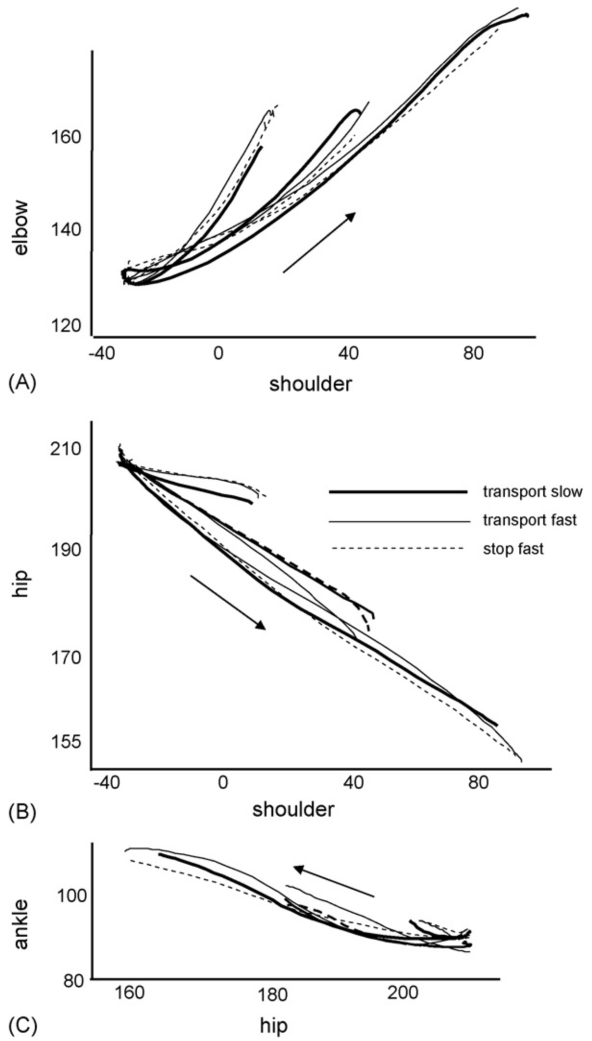

Fig. 5. Angle–angle plots from one representative subject. Each trace is an ensemble average derived from six trials of the reach phase to one target for each of the three movement variations. Arrows indicate direction of movement. (A) The coupling within the upper extremity (elbow–shoulder). (B) The coupling between the upper and lower extremities (hip–shoulder). (C) The coupling within the lower extremity (ankle–hip).

relationship between hip and shoulder motion (Fig. 5B) had one pattern when reaching for the close target and another one when reaching for the middle and far targets. Thus, the angle–angle plots support the results of the PCA and suggest that reaching beyond arm's length alters the coupling in both the reach and postural synergies

4. Discussion

The results of this study indicate that (a) the upper extremities, trunk and lower extremities worked together as a single functional unit during whole body reaching and (b) the movement organization differed for reaches that were within or beyond arm's length. We suggest that these findings can be interpreted as the result of the interaction between two flexible synergies operating in parallel: a reach synergy that transports the body towards the target and a postural synergy that controls interactional forces and maintains the CoM over the base of support.

As has been suggested previously, the involvement in the reach and postural synergies depends on the capacity of each joint to contribute to the achievement of the task [21,24]. When reaching within arm's length, PCA suggested that the reach and postural synergies could be easily separated. Under this condition, the lower extremity joints were coupled into a relatively autonomous postural synergy that functioned to maintain stability. As the reach extended beyond arm's length, the amount of variance accounted for by PC1 increased dramatically, with much higher regression coefficients on the lower extremity joints, indicating that movement of the legs became more strongly coupled to that of the arms and assisted in moving the body forward.

The change in joint movement onset also supports a modification in the organization of the movement. When reaching within arm's length, motion started in the arms, followed by reactive/stabilizing motion in the legs. When reaching beyond arm's length, not only did the legs start moving before the arms, but the order of lower extremity joint onset also changed. Consequently, the postural synergy was modified by the necessity of using the legs to assist in transporting the body to the target.

The suggestion that the lower extremities become more strongly coupled to the arms when reaching can explain discrepant CoM findings in studies on the interactions between posture and movement. Studies using simple arm raises or trunk flexions/extensions have concluded that a primary goal of the postural system is to minimize shifts in the CoM [12,15–18]. When whole body reaching is performed, there is a pronounced shift in the CoM [19–21]. When no target is to be contacted, the postural system can function independently and fulfill the goal of minimizing CoM motion [12–14]. However, when moving to a target, the reach synergy is activated and may incorporate the trunk and legs, depending on the distance to be reached. This suggestion explains why the CoM shifted forward in the present study even when the target was within arm's length. Thus, the amount of CoM displacement may depend on whether the goal of a movement is simply to change the body's configuration or to interact with the environment.

The reach synergy also appeared to be modified by the incorporation of the trunk and lower extremities into the task. Although PCA showed that the coupling between shoulder and elbow remained consistently high when reaching to all three targets, the shoulder–elbow plot indicated that the nature of the angular relationship changed. When reaching beyond arm's length, the ratio of shoulder to elbow displacement increased. This finding has also been observed for trunk assisted reaches performed from a sitting position [23,4]. It was suggested that an active modification of arm joint angles was necessary to maintain a consistent hand trajectory as hip contribution changes. It is likely that a similar compensatory strategy was used during the whole body reaches performed in standing. However, this strategy must also take into account contributions from the knees and ankles during hand transport. Coupling all the joints involved simplifies task planning in that the angular changes required of all joints become a singular function. Thus, the degrees of freedom are reduced and the movement can be accomplished without the need to plan the exact position of all joints across the course of the action.

The idea that synergies are flexible and can be mixed is not new. The study of postural perturbations through support surface translations has shown that synergies involving the hip, ankle can be mixed, depending on the size of the support surface and velocity of the perturbation [9,25,26]. We suggest that this mixing of synergies is not limited to those associated with postural control, but should include synergies involving the upper extremities. When the same set of joints are needed to meet both reaching and stability demands, the nervous system must derive a solution to accomplish both goals simultaneously. Mixing reach and postural synergies in a flexible format provides one solution to this problem.

The flexible nature of the synergies observed in this study also supports the concept of uncontrolled manifolds in which joint configurations are allowed to vary while maintaining higher level performance goals [27–30]. During whole body reaching, there are two primary goals: move the hands to the target and maintain the CoM over the base of support. Due to the redundancy in the degrees of freedom, it appears that a range of equivalent solutions are available within the fundamental synergic patterns that permit flexibility while attaining the primary goals.

The small number of subjects in this study may be considered a limitation that precludes generalizing the results. However, the repeated measures design permitted each subject to serve as her own control. Consequently, it was possible to identify the variance due to individual differences and separate it from the error term which resulted in a more precise analysis and results that were statistically significant. Secondly, the fact that all subjects were female may lead to speculation that the findings are gender specific. Although this may be a possibility, no study has indicated that males and females use different modes of postural control.

In conclusion, we suggest that whole body reaching is organized around the interaction of two flexible synergies working in parallel. When reaching within arm's length, the overlap between the reach and posture synergies is limited. As reach distance extends beyond arm's length, the two synergies interact resulting in a tighter coupling of all joints involved. Consequently, the postural synergy is modified so that the coupling in the lower extremities reflects both the postural stabilizing and body transporting demands of the task.

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