Published in final edited form as:

J Appl Biomech. 2013 April ; 29(2): 235–240.

Multi-Joint Coordination of Functional Arm Reaching: Induced Position Analysis

Wei Liu¹, Jill Whittall², and Thomas M. Kepple³

¹Department of Kinesiology, College of Education, Auburn University, AL

²Department of Physical Therapy and Rehabilitation Science, School of Medicine, University of Maryland, Baltimore, MD

³C-Motion Inc., Germantown, MD

Abstract

Functional arm reaching involves multilinked joints: shoulder, elbow, and wrist. We propose that induced position analysis is a useful analytical tool for multijoint coordination of arm reaching. This method was used to compute the contributions of the net joint moment to the hand position when reaching forward. We describe the method and give examples of validating this model with motion capture data. The shoulder and elbow were prime movers of the arm: both acted together with an “overshoot” and “undershoot” pattern respectively to move the hand forward into the final position.

Keywords

upper limb; arm reaching; multijoint coordination; induced position

Reaching for an object with the arm is a goal-directed and functional motor task that integrates the nervous and musculoskeletal systems, requiring simultaneous coordination of the wrist, elbow, and shoulder joints. The central nervous system must control this complex coordination by managing kinetic factors to achieve the desired end positions through kinematics. Determining the relationship between the joint kinetics and position of the hand is important in understanding the underlying neuromotor processes of arm reaching.

Previous studies have shown that the interaction effect between two adjacent joints plays a very important role in activities such as reaching,^{1–5} drawing^{6,7} and throwing.⁸ In this paper we propose an induced position analysis (IPA) method⁹ that may provide additional insight into coordination of multijoint functional arm reaching movement. This is because, during the execution phase of any multijoint task, a moment at a joint will act to accelerate all of the other joints of the body and not only the adjacent joint.¹⁰ In other words, joints are controlled dependently in a coupled manner. This mechanical coupling approach, termed

induced acceleration analysis (IAA) is the fundamental basis to estimate the relationship between joint kinetics and hand position during functional arm reaching.

Although IAA is a technique that allows us to directly determine the relationship between joint kinetics and joint kinematics, to date IAA has mainly been limited to studying lower extremity control strategies.^{11–15} At this point no model exists that directly determines which net joint moments control hand position during functional arm reaching. In this paper, we first apply an IAA to a functional arm reaching task and then extended the IAA to obtain an IPA of the hand. This article represents a step forward in examining the multijoint coordination during functional arm reaching because the IPA allows us to, for the first time, directly determine how the joint moments produce the measured kinematics of the hand along a path.

Methods

Ten right-handed healthy participants (6 women, aged 28–58 y, mean 37.8 y) were enrolled. Written informed consent was obtained in compliance with Institutional Review Board requirements at the University of Maryland, Baltimore. Participants were seated at a table with an $18 \times 15 \times 9$ cm box in front of them at a distance corresponding to their arms' maximum voluntary reach excursion. At the starting position, subjects were asked to place their right hand on the surface of the table with 90 degree elbow flexion and shoulder flexion of 0 degrees as a neutral starting condition (Figure 1). They were instructed to reach out with the right hand to contact the right side of the box and come to a complete stop at their preferred speed. They performed 4 trials.

A Flock of Birds magnetic tracking system (Ascension Technology, Burlington, VT) was used to record the functional reaching task with a sampling rate at 50 Hz. Sensors were attached on the right hand, forearm, upper arm, and trunk. Right-handed local segmental and laboratory coordinate system were constructed so that the X-axis is directed laterally to the right, the Y-axis is directed anteriorly, and the Z-axis is directed superiorly.

A customized biomechanical model of upper extremity was created in SD/FAST software (PTC Software, Inc). The model was configured with 4 segments with local X-Y-Z coordinate system and their anthropometric information. The 4 segments included a trunk, and right upper arm, a right forearm, and a right hand with a total of 6 degrees of freedom. The wrist joint was modeled as a pin joint, the elbow as a universal joint, the shoulder as a gimbal joint, and the trunk was fixed relative to ground. Figure 2 shows the IAA procedure. The SD/FAST software generated two C language source files containing the configuration of the model. The SD/Fast C code was compiled as a MEX library, which allowed the code to be accessed in the same MATLAB environment in which the kinematics variables were calculated in Euler angles and kinetics variables (joint moments) were derived by using Newton-Euler equations (inverse dynamics model).¹⁶ Once the contribution of each net moment to the acceleration of the center of mass of the hand was estimated by IAA, then the total observed angular accelerations of hand position can be reconstructed by summing the individual induced accelerations. The summation of induced accelerations can be integrated over the time interval to get induced velocity; the summation of induced velocity then can be

integrated over the time interval to get induced position. Thus, IPA represents the changes in hand position due to the contribution of the net moments acting on shoulder, elbow, wrist, and the position changes produced by gravity.

Dependent variables included the final position of the center of mass of the hand obtained from the motion capture (Mocap) data, the final position from the IPA and the root mean square (RMS) error of the IPA model determined from the absolute difference in mean forward hand position as measured by the Mocap and IPA output at the last frame.

Results

The validity of the IPA was examined by both computing RMS error throughout the entire movement and by the last frame absolute difference between the IPA output and the center of mass of the hand position obtained from the Mocap data. The mean RMS error was 0.026 m (SD = 0.003 m), representing the 12.1% of the average reaching distance, and the mean last frame error was 0.053 m (SD = 0.005 m).

The acceptable error values indicated the validity of the IPA. Data for the subject with the smallest error (Figure 3a) and for the subject with the error closest to the mean RMS error (Figure 3b) are illustrated in Figure 2. This shows close agreement for the center of mass of hand trajectory when comparing the IPA output and the Mocap data.

The pattern of induced hand position from net moments acting on shoulder, elbow, wrist, and gravity (Figure 4a), indicated that the shoulder was the largest contributor to hand movement in the forward direction while the elbow played a significant role in contributing to hand movement in the backward direction. Only a minimal contribution was observed from the wrist and gravity. The shoulder generally moved the hand to “overshoot” the target at the final position while the elbow counterbalanced the shoulder to “undershoot” the reaching target at the final position (Figure 4a).

Discussion

The IPA approach was extended to look at multijoint coordination in arm reaching. This method not only includes the properties of the entire mechanical linkage model, but also provides a direct solution to estimate the source of hand position produced by the net moment. The performance of IPA was tested by comparing Mocap data, the low RMS value illustrating validity of the model. It is important to note that angular net moments are “transformed” into a linear position; the IPA results are dependent on orientation of the arm during reaching. With our standardized start and end positions, the kinematics of our participants was very consistent, which was reflected by smaller RMS error (mean: 0.026 m; SD: 0.003 m).

The arm control strategy revealed by the IPA may be termed a directional control principle because the shoulder and elbow net moments contribute to the hand reaching in different directions. Previous studies were able to find that the shoulder and elbow joint coordinate together to make sure the hand can reach the target,²⁻⁴ but a potentially misleading conclusion may be that the shoulder and elbow joint are both contributing to hand reaching

in the same forward direction. The directional control principle, therefore, adds additional insight to our current understanding of motor control of arm reaching. This resultant motor outcome we observed is a summed effort from all other joints. The directional control principle demonstrated that under the summation effort, the shoulder and elbow played major roles but in opposite directions.

An important limitation of this study is the fact that the kinematic and kinetic inputs to IAA/IPA were computed based on a model that allowed 9 degrees of freedom at all three joints. The IAA/IPA model used in this study contained joint constraints such that the 3 joints contained a total of 6 degrees of freedom. This mismatch between the input and IAA/IPA models is possibly responsible for the observed measurement errors. However, as demonstrated in Figure 4b, the last frame source of error was very small compared with the induced hand position due to the contribution of the net moment acting on shoulder, elbow, wrist, and gravity. This indicates that this potential source of error is a minor issue.

In conclusion, we have demonstrated how IPA can be used to potentially aid our understanding of the motor control of arm reaching in a healthy population. To our knowledge, this is the first time this approach has been used to analyze arm reaching data. The validated IPA approach may allow us to detect new hand position control strategies. In the future, this approach can be extended to analyze patient populations such as individuals with stroke to determine compensatory control strategies.

Acknowledgments

This study was supported by NIA Claude D. Pepper Older Americans Independence Center P60-AG12583 (A.P. Goldberg, PI) and by NIDDR H133G010111 (J. Whittall, PI).

References

1. Hollerbach MJ, Flash T. Dynamic interactions between limb segments during planar arm movement. *Biol Cybern.* 1982; 44(1):67–77. PubMed. 10.1007/BF00353957 [PubMed: 7093370]
2. Bastian AJ, Martin TA, Keating JG, Thach WT. Cerebellar ataxia: abnormal control of interaction torques across multiple joints. *J Neurophysiol.* 1996; 76(1):492–509. PubMed. [PubMed: 8836239]
3. Sainburg RL, Kalakanis D. Differences in control of limb dynamics during dominant and nondominant arm reaching. *J Neurophysiol.* 2000; 83(5):2661–2675. PubMed. [PubMed: 10805666]
4. Galloway JC, Koshland GF. General coordination of shoulder, elbow and wrist dynamics during multijoint arm movements. *Exp Brain Res.* 2002; 142(2):163–180. PubMed. 10.1007/s002210100882 [PubMed: 11807572]
5. Yamasaki H, Tagami Y, Fujisawa H, Hoshi F, Nagasaki H. Interaction torque contributes to planar reaching at slow speed. *Biomedical Engineering Online.* 2008; 7:27.10.1186/1475-925X-7-27 [PubMed: 18940016]
6. Ketcham CJ, Dounskaia NV, Stelmach GE. Age-related differences in the control of multijoint movements. *Motor Control.* 2004; 8(4):422–436. PubMed. [PubMed: 15585898]
7. Tseng YW, Scholz JP. Unilateral vs. bilateral coordination of circle-drawing tasks. *Acta Psychol (Amst).* 2005; 120(2):172–198. PubMed. 10.1016/j.actpsy.2005.04.001 [PubMed: 15939387]
8. Hirashima M, Kudo K, Watarai K, Ohtsuki T. Control of 3D limb dynamics in unconstrained overarm throws of different speeds performed by skilled baseball players. *J Neurophysiol.* 2007; 97:680–691. PubMed. 10.1152/jn.00348.2006 [PubMed: 17079349]

9. Anderson FC, Goldberg SR, Pandy MG, Delp SL. Contributions of muscle forces and toe-off kinematics to peak knee flexion during the swing phase of normal gait: an induced position analysis. *J Biomech.* 2004; 37(5):731–737. PubMed. 10.1016/j.jbiomech.2003.09.018 [PubMed: 15047002]
10. Zajac FE, Gordon ME. Determining muscle's force and action in multi-articular movement. *Exerc Sport Sci Rev.* 1989; 17:187–230. PubMed. [PubMed: 2676547]
11. Kepple TM, Siegel KL, Stanhope SJ. Relative contributions of the lower extremity joint moments to forward progression and support during stance. *Gait Posture.* 1997; 6:1–8.10.1016/S0966-6362(96)01094-6
12. Pandy MG. Computer modeling and simulation of human movement. *Annu Rev Biomed Eng.* 2001; 3:245–273. PubMed. 10.1146/annurev.bioeng.3.1.245 [PubMed: 11447064]
13. Fregly BJ, Zajac FE. A state-space analysis of mechanical energy generation, absorption, and transfer during pedaling. *J Biomech.* 1996; 29(1):81–90. PubMed. 10.1016/0021-9290(95)00011-9 [PubMed: 8839020]
14. Siegel KL, Kepple TM, Stanhope SJ. Using induced accelerations to understand knee stability during gait of individuals with muscle weakness. *Gait Posture.* 2006; 23:435–440. PubMed. 10.1016/j.gaitpost.2005.05.007 [PubMed: 16098747]
15. Zajac FE, Neptune RR, Kautz SA. Biomechanics and muscle coordination of human walking. Part I: introduction to concepts, power transfer, dynamics and simulations. *Gait Posture.* 2002; 16(3): 215–232. PubMed. 10.1016/S0966-6362(02)00068-1 [PubMed: 12443946]
16. Winter, DA. *Biomechanics and Motor Control of Human Movement*. 3rd. New York: John Wiley & Sons; 2005.

Figure 1.
Schematic diagram of arm reaching experimental setup.

Figure 2.

A block diagram of the IAA procedure (note that the IPA was obtained from double integration of the output of the IAA.).

Figure 3.

A. Data for the participant with the best agreement between the IPA and motion capture (Mocap) hand trajectory. **B.** Data for the participant whose error

between IPA output and motion capture (Mocap) data were the closest match to the mean hand trajectory error.

Figure 4.

A. Single representative data of induced hand position pattern from net moment acting on shoulder, elbow, wrist, and gravity during the arm reaching Forward Direction (+), Backward Direction (-). **B.** Bar graph of single representative participant data of final induced hand position from net moment acting on shoulder, elbow, wrist, gravity and last frame error.