USE OF POTENTIAL ENERGY TO ANALYSE UPPER LIMB ACTIVITIES OF DAILY LIVING

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ABSTRACT

Ten men and ten women accomplished six brief, work-oriented activities of daily living (ADL's) including zipping, screwdriver bit changing, cutting with knife and fork, hammering, folding and inserting paper in an envelope, and tying a string. During these, trajectories of skin-mounted markers on anatomical landmarks of the upper limbs were recorded with an VICON 140 motion analysis system. Combinations of these markers were used to determine the location and orientation of the upper arms, forearms and hands. With known anthropometric data, segmental mechanical energy was calculated. Since kinetic energy components were much less than potential energy components during all of the ADL's studied, total segmental mechanical energy was estimated using potential energy alone. A composite measure of upper limb potential energy normalised on body mass distinguished the six tasks and the role of arm dominance within these tasks. This indicates potential energy's sensitivity for analysing qualitatively observed motion variations.

Keywords: quantitative task analysis

L'ANALYSE DES ACTIVITÉS DE LA VIE QUOTIDIENNE DES MEMBRES SUPÉRIEURS À PARTIR DE L'ÉNERGIE POTENTIELLE

RÉSUMÉ

Dix hommes et dix femmes ont accompli six brèves activités de nature quotidienne (ouvrir une fermeture éclair, changer un foret, trancher avec un couteau et une fourchette, marteler, plier et insérer une feuille dans une enveloppe, et nouer un fil. Lors des activités les trajectoires des marqueurs sur la peau des membres supérieurs étaient enregistrées par un système VICON 140. Des combinaisons de marqueurs ont permis de calculer les lieux des principaux segments des membres supérieurs (le bras, l'avant-bras et la main). L'énergie mécanique des segments était calculée à l'aide des données anthropométriques. Puisque l'énergie cinétique était beaucoup moindre que l'énergie potentielle durant toutes les activités étudiées, l'énergie potentielle estimait l'énergie mécanique totale. Une mesure composée d'énergie potentielle normalisée sur la masse du corps distinguait les six tâches et le rôle du bras dominant et non-dominant lors de ceux-ci. Ceci signifie la capacité de l'énergie potentielle pour analyser des variations qualitatives.

Mots clés : analyse quantitative, tâche

INTRODUCTION

Human upper limbs are very versatile, allowing accomplishment of diverse and complex motions and tasks. Indeed, even during very brief activities of daily living (ADL's) a variety of upper limb motions and postures are used, some of which may be associated with development of musculoskeletal disorders (MSD). To distinguish variables that are significant, ergonomic task analysis requires objective, quantitative measurements of motions and methods used during working tasks. To date however there is no single accepted method for this quantitative analysis.

Efficiency is often used as a way to quantify differences in ADL's. Biomechanical efficiency compares movement amplitude and orientation, to account for muscular effort, joint involvement and range of motion. Measuring movement efficiency itself poses some problems since external physical work measurement (with a force-plate) is only clearly related to metabolic energy by calorimetry when considering full body, large amplitude movements (3). Calorimetry and oxygen uptake only consider the body as a whole, excluding isolation of the roles of the relatively small upper limbs. Thus such methods are insensitive to the largely horizontal and small segment movement of greatest interested in ADL ergonomics.

Mechanical energy includes both kinetic (movement based) and potential (height based) components to define the energy of a body. Segmental mechanical energy has been used to quantify the body at work, without focussing exclusively on the comparison of upper limb activities. Mechanical energy analysis may consider individual or grouped segments and be used as a comparative tool (1).

This study focuses on how composite segmental mechanical energy over the upper limbs can compare brief, qualitatively different goal-oriented ADL's.

METHOD

Quantitative motion data were recorded at 60 Hz using a 3-camera VICON 140™ optometric motion analysis system for ten men and ten women of working age (18 to 62 years old) during six bi-manual desk-top activities of daily living. Activities were chosen to represent different levels of required dexterity, force, and arm segment involvement (see Table 1).

Each task was recorded four times, twice viewing the left side and twice the right side. Instructions were the same for all repetitions of each task, and subjects were asked to choose and maintain the same method for each task throughout the recording session. Tools were placed at fixed percentages of maximum reach envelope on the desk surface. Chair height was adjusted to locate the desk surface approximately 3 cm below the elbow while the subject sat in a relaxed posture. A footstool was used to maintain full contact of the feet on the floor under the desk surface with the knees flexed to 90°.

Tasks were presented in the order given in Table 1 over all four repetitions, corresponding to increasing difficulty for an upper limb prosthesis user. The side to be recorded first was chosen randomly. Trajectories were identified for three non-collinear skin-mounted markers on each of the segments (see Figure 1). This allowed segmental calculation of both kinetic and potential energy components where marker trajectories were consistently visible. When gaps in marker trajectories were brief (less than eleven consecutive samples, or 0.17 seconds in duration) missing data were filled by linear interpolation. Subsequently, data were filtered using a 6Hz forward and backward low pass Butterworth filter, having confirmed that over 99% of the marker trajectories' power spectrum was less than 2 Hz for all of the recorded tasks.

Table 1. Motion characteristics of the activities of daily living tested

Tasks	Expected motion characteristics
1) zipping and unzipping the main U-shaped zipper on a backpack	- slow movement at relatively constant height - one arm holds while other pulls; roles may reverse - pulling hand may pass above or below holding hand
2) changing a screwdriver bit	- small amplitude, slow movement most frequently involving the fingers, wrist and forearm - similar height to hold screwdriver and manipulate bits
3) cutting two slices of a plasticene "steak", picking them up and placing them on an adjacent plate	- one hand holds fork above steak; cutting arm is maintained lower and movement involves entire arm - both arms are used to place slices
4) hammering a nail 0.5 inches into a block of wood	- one arm (non-dominant) holds the nail (or block of wood) while second arm hammers - hammering arm consistently higher, and much more dynamic than holding arm
5) folding a sheet of paper and placing it in an envelope	- similar heights and velocities for both arms - mostly gross arm movements - orientation and height varies during insertion
6) tying a knot and a bow with a string	- both arms are maintained at similar heights - mostly finger and horizontal movements

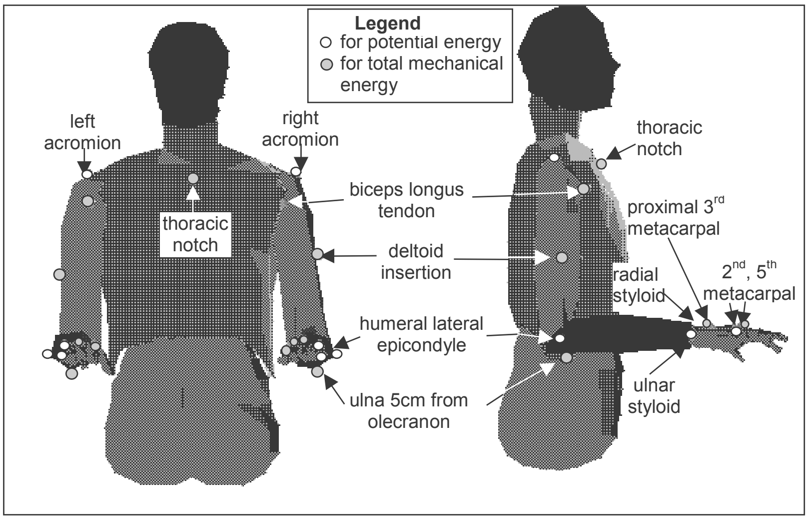

Figure 1. Skin-mounted marker locations

Notably, kinetic energy components were found to be consistently much smaller than potential energy components, with the range of kinetic energy being on average 51 times less than that of potential energy. This tendency was observed for all six recorded ADL's. In addition, potential energy is simpler to calculate than kinetic energy since it does not require calculation of velocity or knowledge of the complete three-dimensional orientation of the body over time. As a result, potential energy is used here to estimate mechanical energy and analyse motion quantitatively during working tasks.

To calculate segmental potential energy, a single marker was used at each of the proximal and distal ends of each of the principal upper limb segments (upper arm, forearm, and hand). From each pair of markers, segmental centre of gravity was estimated assuming fixed joint centre locations relative to adjacent segment centres of gravity. Knowing the vertical component of the segmental centres of gravity, and defining segmental mass based on measured anthropometry and published data (2), segmental potential energy was calculated.

A composite summary measure of potential energy (PE) was defined as

$$average\_PE = \sum_{segments} \frac{\sum_{i=1}^{n} PE_i}{n} \quad [J] \qquad [1]$$

where i is the sample number
n is the maximum sample number
segments = upper arm, forearm and hand

This value was furthermore normalised on individual total body mass and acceleration due to gravity, defining a weighted composite upper limb "height", h^*, to allow comparison across the tested population:

$$h^* = \frac{average\_PE * 1000}{body\_mass * g} \quad [mm] \qquad [2]$$

where 1000 is a scaling factor to report h^* in millimetres rather than metres.

Note that *relative* h^* was calculated by subtracting the minimum PE value from average PE for each segment over the task recording.

ANALYSIS OF RESULTS

Statistical analysis of the results across the subject population explored the importance of subject, task, gender and arm dominance using SPSS (release 10.05). Men tested were found to have somewhat higher and more variable h^* values than women. While handedness did not significantly affect h^*, left-handed subjects overall had less variable and slightly lower h^* values than right-handed subjects. More interestingly, the non-dominant arm had lower h^* valued than the dominant arm. Task was highly significant in determining h^* values, as was subject (although subject ceased to be significant when analysing *relative* h^*). A multi-factor analysis of variance considering task, task * arm dominance, subject, and subject * arm dominance, all factors were highly significant ($p<0.01$) in determining h^*. Pair-wise post-hoc comparisons using Tukey's Honestly Significant Difference test found that hammering presented the greatest *relative* h^* values and was significantly higher ($p<0.05$) than each of the tying, folding, or bit changing tasks (see Table 2). Furthermore, the dominant arm during hammering had significantly higher *relative* h^* than all other activities with either arm, except for the non-dominant arm during cutting (see Table 3).

Table 2. Tukey pair-wise comparisons of mean difference in *relative h by task for 0.05 significance (*) and 0.01 significance (**) for matched non-domant /dominant data**

Task	fold	tie	Zip	cut	hammer
bit change[a]	0.32	0.77**	1.11**	1.36**	1.48**
fold	-	0.45	0.79**	1.04**	1.16**
tie	-	-	0.34	0.59	0.71*
zip	-	-	-	0.25	0.37
cut	-	-	-	-	0.12

[a]The minimum mean relative *h** value was 1.63 mm for screwdriver bit changing.

Table 3. Tukey pair-wise comparisons of mean difference in *relative h by task and dominant arm view for 0.05 significance (*) and 0.01 significance (**)**

Task x Viewed dominance[a]	bit – dom	fold – nd	fold – dom	hammer – nd	tie – dom	zip – nd	tie – nd	cut – dom	zip – dom	cut – dom	hammer – dom
bit –nd[b]	0.45	0.55	0.56	0.63	0.83	1.16*	1.17*	1.31**	1.59**	1.91**	3.00**
bit – dom	-	0.10	0.10	0.18	0.37	0.70	0.71	0.84	1.14*	1.45**	2.54**
fold – nd	-	-	0.001	0.08	0.27	0.61	0.61	0.75	1.04	1.35**	2.45**
fold – dom	-	-	-	0.08	0.27	0.61	0.61	0.75	1.04	1.36**	2.44**
hammer – nd	-	-	-	-	0.19	0.53	0.53	0.67	0.96	1.28**	2.36**
tie – dom	-	-	-	-	-	0.33	0.34	0.48	0.77	1.08	2.17**
zip – nd	-	-	-	-	-	-	0.01	0.14	0.43	0.75	1.84**
tie – nd	-	-	-	-	-	-	-	0.14	0.43	0.75	1.84**
cut – dom	-	-	-	-	-	-	-	-	0.29	0.61	1.69**
zip – dom	-	-	-	-	-	-	-	-	-	0.32	1.40**
cut – nd	-	-	-	-	-	-	-	-	-	-	1.09
hammer –dom	-	-	-	-	-	-	-	-	-	-	-

[a]dom = dominant arm viewed; nd = non-dominant arm viewed
[b]The minimum value of *relative h** was 1.39 mm for the non-dominant arm during screwdriver bit changing.

DISCUSSION

These results indicate that a composite measure of potential energy across upper limb segments is sensitive to qualitatively-observed variations in motion characteristics across tasks and between dominant and non-dominant arms. These potential energy measurements provide a framework for comparison of activities. Since they require just two markers per segment and the method is mathematically robust, it may be used in a clinical setting to compare individuals in different populations, including those with upper limb disabilities or functional limitations. Future studies will concentrate on simultaneous recording of both upper limbs allowing for study of qualitative motion or movement variations within a given task and subject.

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