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MAGNITUDES AND TEMPORAL SEQUENCING OF LOAD KINEMATICS AND KINETICS FOR SINGLE-HANDED PULLS

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ABSTRACT

This paper provides data regarding kinematics and kinetics during single-handed, submaximal pulls about various locations in the frontal plane for three loads (6, 12 and 18% lean body mass). Pulls were executed at two relative heights (elbow and eye) through two parasagittal planes also relative to subject morphology. Results indicate that in most cases load and pull location influence the occurrence of measured kinetic variables within a pull cycle but have little effect on the magnitude of these values. Findings from this study suggest that analyses of kinematic and kinetic movement histories may be required for a better understanding of the mechanical loading profiles upon operators engaged in such manual materials handling activities.

INTRODUCTION

Micro-ergonomic investigations generally focus on the relationship between the physical characteristics of the task (external factors) and the biophysical and psychophysical responses of the operator (internal factors). While a relationship certainly exists between these external and internal factors for any manual materials handling (MMH) event, the response of one due to changes in another often cannot be reliably predicted. Understanding the operator-machine interface is necessary to ensure compatibility between the two. Success in this respect should minimise the risk of operator injury and improve productivity.

Past research into pulling activities has focused primarily on workstation and equipment design factors and their effects on maximal pulling exertions. While this focus is certainly of major benefit in a workstation design context, it has not adequately served ergonomists in identifying safe pulling practices or provided needed insight into those factors which contribute to acute or chronic soft tissue injuries (van der Beek **et al**., 1999). Deriving guidelines that delineate allowable limits for pulling exertions with respect to workstation-related factors would be of tremendous value to ergonomists and industrial engineers. However, incomplete description of any task-related variable that requires muscular effort and imposes biomechanical demands upon the operator will result in a flawed estimation of the soundness of any protective guidelines (Westgaard and Winkel, 1996).

The main external factors that influence the manner in which an operator exerts a pull force include: manner of strength expression (isometric, isokinetic, isoinertial); magnitude of the load; location of the pull origin; one-handed versus two-handed pulls; and posture characteristics (fixed feet, standing, sitting). Kumar **et al**. (1995) suggested that a failure to account for such factors in an experimental design could produce differences in the region of 60% when comparing research results for pulling activities. It seems there exists a complex interaction between the machine and operator when creating a horizontal force.

The literature that has examined operator responses during pull exertions has focused on prediction of stresses on the anatomy, particularly structures of the lower back (Lee **et al**., 1989; Kumar, 1994). While this approach has provided some insight into probable injury mechanisms, data from seemingly similar experimental protocols tend to be highly variable. This is a direct result of the assumptions made and limitations of the different biomechanical force prediction models.

Imrhan and Ayoub (1990) proposed that future research should focus less on predictive kinetic models and more on the importance of the kinematic characteristics of the activity. As in the lifting literature, numerous research studies on pulling activities have yet to provide guidelines known to eliminate or reduce the incidence of musculoskeletal injury. Insight into common coordination strategies should lead to a better understanding of those pulling activities that predispose a person to injury and/or influence the ability to coordinate the production of the required forces.

Recent evolutions in technology have improved the capacity for ergonomists to collect time-series data. While providing a better description of the system under examination, a better understanding of how to properly analyses the output data is needed. This analytical hurdle increases the temptation for a researcher to summarize these data mathematically, generally employing simple descriptions of central tendency and variability, and then submitting these data to appropriate statistical analyses.

The purpose of this paper is to gain a better understanding of the effects of workstation factors on load kinematics and kinetics, and to demonstrate that employing summary measures of time-series profiles can lead to an incomplete understanding of the demands upon an operator.

METHODOLOGY

Subjects

Twenty healthy adult males who reported no current or past musculoskeletal injuries and were right hand and right lower limb dominant were recruited to participate in the study.

After the experimental protocol was explained and subjects offered an opportunity to ask questions, informed consent was obtained. Subjects were then given an opportunity to attempt the pull tasks under approximated experimental conditions. Following this acclimatization period, subject anthropometric measurements were recorded (see Table I). Detailed description of the anthropometric measurement procedures can be found in Pheasant (1988). Body density was estimated using the procedure described by Jackson and Pollock (1978) and percentage body fat was calculated by the Siri formula (Siri, 1956). Subjects were requested to return the following day to participate in the formal data collection session.

TABLE I: Summary anthropometrics for twenty subjects.

Variable	Mean	SD	CV	Min	Max
Age (Yrs)	22.0	2.0	9.2	19.0	26.0
Mass (kg)	83.3	12.4	14.9	65.4	114.6
Body Fat (%)	12.9	5.5	42.6	5.9	24.2
Lean Body Mass (kg)	72.0	7.6	10.5	60.1	86.9
Stature (mm)	1853.7	42.5	2.3	178.9	194.8
Elbow Height (mm)	1157.5	28.4	2.5	110.1	124.3
Eye Height (mm)	1735.8	46.8	2.7	167.3	182.5
Humerus Length (mm)	380.2	16.4	4.3	35.0	41.2
Shoulder Width (mm)	482.8	42.6	8.8	35.2	54.8
Hip Width (mm)	355.8	19.0	5.3	31.9	41.2

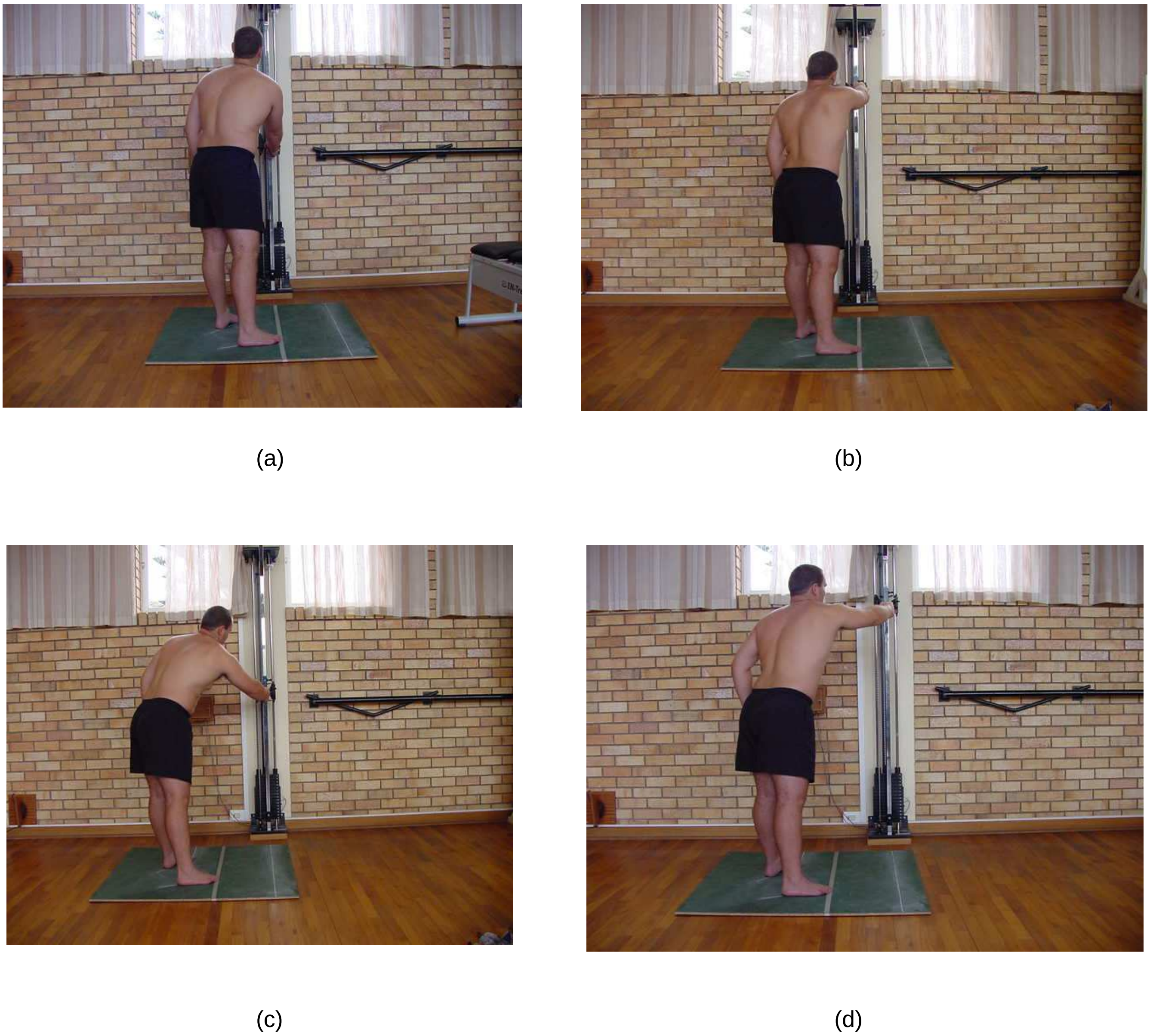
Experimental Task

This study examined one-handed pull exertions originating from four locations about the frontal plane. These pull origins were described within a standard planar system and were relative to the morphology of each subject. Two pull heights were tested, orbital height and elbow height, through two sagittal planes. The sagittal planes occurred through the gleno-humeral joint center when the arm was held relaxed at the subject's side and another plane lateral to this, at a distance defined by the length of the center of the subject's gleno-humeral joint to the center of the elbow joint. Figure 1 (a,b,c,d) illustrates these locations.

Each subject was required to exert these pulling action against loads of 6, 12 and 18% of lean body mass. The magnitudes of these loads were based on suggestions made by MacKinnon (1999) and from extensive pilot work completed prior to the commencement of the study. The subject was requested to maintain a grip on the handle attached to the load in a vertical orientation throughout the duration of each trial.

It was necessary to control several variables during the collection of the data. Foot placement was prescribed for each subject and kept constant for each experimental condition. The spatial orientation of each foot was positioned as follows: the left big toe was positioned a distance of 20% of stature from the frontal plane of origin of pull and a distance of 10% stature from the sagittal plane containing the line of pull and the longitudinal axis of the left foot angled so it was 55 degrees relative to the right horizontal of a frontal plane parallel to the plane containing origin of pull. The big right toe was positioned a distance of 45% of stature from the frontal plane of origin of pull and on the sagittal plane containing the line of pull and the longitudinal axis of the right foot angled at 35 degrees relative to the right horizontal of a frontal plane parallel to the plane containing origin of pull. These foot orientations were based upon recommendations by MacKinnon (2001). Subjects were asked to pull the handle in the horizontal plane a distance equivalent to 20% of their stature. A visual cue was clearly demarcated on the rail guiding the load excursion.

Subjects were free to choose the tempo at which the pull cycles were executed, although subjects were encourage to maintain temporal consistency with a particular condition. No auditory or visual prompt was given to the subject in this respect. The subject was requested to provide a discernable pause between each concentric-eccentric pull cycle, but not to hesitate in the transition between the concentric and eccentric phases.



(a) (b)

(c) (d)

Figure 1: Location of Pull Origins: (a) Elbow height/Sagittal plane dissecting gleno-humeral joint – referred to as “Elbow-In” in text, (b) Eye height/Sagittal plane dissecting gleno-humeral joint– referred to as “Eye-In” in text, (c) Elbow height/Sagittal plane located laterally– referred to as “Elbow-Out” in text, (d) Eye height/Sagittal plane located laterally– referred to as “Eye-Out” in text.

Apparatus

An En-tree isoinertial pulley system (Enraf Nonius B.V., Holland) was employed to provide a horizontal resistance against which the subject exerted a concentric-eccentric pulling action. The investigator could select loads in 0.5 Kg increments. In order to expose the subject to the required 6, 12 and 18% lean body mass loads, an appropriate additional mass was secured to the top weight plate of the system. The height of the handle, attached to the load via a cable system, was adjustable to 20 mm intervals. The device measured load displacement via a series of potentiometers at a sampling frequency of 100 Hz and had a measurement resolution of 2 mm. Velocity- and acceleration- time profiles were derived employing a finite differences algorithm contained in the software purchased with the device. Force- and power-time profiles were then calculated from these data.

Experimental Procedure

A randomised block factorial design was employed in this study. Two independent variables were defined: (1) pull load and (2) location of pull force about a subject relative position in the frontal plane.

The subject was asked to stand on a slip resistant surface that demarcated the standardised foot positions. The feet were then aligned to the investigator's satisfaction. As in the session during which anthropometric data were collected, the subject was provided ample time to familiarise himself with the data collection protocol and attempt all conditions prior to actual data collection. Data collection did not commence until both subject and experimenter were satisfied that the subject could competently execute the task.

The subject was asked to exert approximately 10 pulls for each condition. Attempts were made to select five consecutive efforts for subsequent analysis. Five repeated measures have been reported to be sufficient to obtain an unbiased estimated of the demands imposed on the subject (van der Beek **et al.**, 1999). Subjects were given a minimum of 150 seconds of rest between each trial in order to minimise the effects of fatigue. Load and pull force locations were randomly presented to each subject in order to eliminate any order effects.

Statistical Analyses

A two-factor analysis of variance was employed to assess the effect of load and pull location on the load kinematics. If a significant difference was detected for either of the main effects the Tukey *post hoc* analyses method was employed using a 95% simultaneous confidence interval for specified linear combinations.

RESULTS and DISCUSSION

There were no significant differences in the load displacements, pull times and peak and mean pull velocities between load and pull locations. As to be expected, there were significant differences for peak and mean pull forces (both with $p < 0.0001$) and peak and mean pull powers (both $p < 0.0001$) between all load conditions. However, peak force and power magnitudes were consistent between the four pull locations within a load condition.

Load and pull location had no significant effect on when the peak force occurred during the pull cycle. On average, the peak force occurred within 21.6% (SD=0.8) from the start of the movement time. This peak force represents the maximum force required to overcome the inertia of the load. These initial forces are thought to be important in the understanding of the cumulative mechanical exposure upon an operator (van der beek **et al.**, 1999) and more specific research into the early stages of a pull motion is needed. Subsequently the force exerted on the handle decreased as the load gained momentum.

While the distance through which the load was manipulated was controlled, subjects were free to choose the speed with which to execute the movement. While it is interesting, from a motor control perspective, that there were no significant differences in the times and speeds for the subjects across load and pull location conditions, there were load and pull location effects on when peak velocity and power values occurred within the time-series histories. These data are summarised in Table **II**.

Table II: Peak kinematic and kinetic values and relative time in pull cycle that each occurred.

Load	Location	Force (N)	(% cycle)	Velocity ($m.s^{-1}$)	(% cycle)	Power (W)	(% cycle)
6%	Elbow-In	68.8	21.6	1.34	50.0	72.2	42.1
	Elbow-Out	66.3	22.0	1.33	54.8	69.9	47.1
	Eye-In	67.9	22.0	1.32	51.1	71.0	42.8
	Eye-Out	66.1	21.8	1.32	54.5	69.5	47.2
12%	Elbow-In	127.6	21.6	1.29	50.2	130.3	42.8
	Elbow-Out	121.6	20.2	1.21	54.7	119.3	48.4
	Eye-In	122.8	21.1	1.21	49.8	119.0	42.9
	Eye-Out	120.2	20.7	1.20	55.4	116.9	49.3
18%	Elbow-In	185.4	21.7	1.32	52.6	193.7	45.1
	Elbow-Out	182.8	21.4	1.29	55.6	186.6	48.7
	Eye-In	183.5	22.2	1.27	51.9	185.4	44.8
	Eye-Out	181.2	23.4	1.29	57.1	185.9	50.3

Both load and pull location had an effect upon when the peak pull velocity occurred ($p = 0.0087$ and $p < 0.0001$ respectively). *Post hoc* analyses indicated that when the peak pull velocity occurred was significantly different for the 12% and 18% mass loads. It was also observed that all of the “In” versus “Out” pair-wise comparisons of pull location were responsible for the significantly differences in these values. Pull exertions through a sagittal plane located at the glenohumeral joint (Elbow-In and Eye-In positions) occurred at approximately 50.9% of the pull cycle while efforts upon handle locations located more laterally (Elbow-Out and Eye-Out positions) occurred 55.3% into the movement cycle.

The timing of the peak pull power demonstrated significant difference due to load ($p = 0.0047$) and pull location ($p < 0.0001$). *Post hoc* analyses indicated that the 6% and 18% mass loads were significantly different. Similar to the velocity profiles, the “In” versus “Out” locations were significantly different. Peak power for the “In” locations occurred at approximately 43.4% of the pull cycle, compared to 48.5% of the pull time for the “Out” locations.

Across subjects and conditions, peak power values preceded peak velocity values by 7.2% (SD=0.6) of the total movement time, occurring approximately 46.0% (SD=2.9) into the pull cycle. Pull location within the two sagittal planes monitored demonstrated slightly different temporal sequencing. For the “In” positions, peak power values occurred 7.5% earlier during the movement cycle than the peak velocity values, and in the “Out” positions this difference was reduce to 6.9%.

Hill (1938) described variations in isolated muscle power as a function of both force and velocity. Because force- and power-velocity relationships characterise the dynamic capability of muscle, they have a significant impact on the performance of movement. Even with respect to full, whole-body movements with complex kinematic patterns there seems to be a relationship between the kinetic measures describing the load. Interestingly, operator posture, which ultimately influences relative segment orientation and thus muscle-tendon unit length, seem to mediate the relationship between measures of outcome load force, velocity and power measures.

CONCLUSION

Representing time-series profiles using average values can mask important differences between experimental conditions. These data illustrate that even though there were no statistical differences between typical kinematic descriptors of load motion (*i.e*. distance pulled, time of pull and speed of pull), the temporal sequencing was significantly effected by load mass and origin of pull. More importantly, how subjects coordinated load kinetics was dependent upon the location of the parasagittal plane containing the origin of the pull. This has significant implications for the design of workstations or equipment that requires applications of pull forces requiring specific amounts of velocity or power, such as motors that are ignited via a pull cord (*e.g.* Garg **et al**., 1988). The differences in which these subjects timed pull exertions for the “In” versus “Out” will likely effect musculo-skeletal loading histories. This further complicates understanding of the aetiologies of work-related injuries due to MMH activities that involve pull exertions.

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