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The effects of dynamic movement on seated reach arcs

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The objective of this study was to determine the relationship between movement of the low back and shoulder during a normal seated reach and the reach arc estimation equations found in literature. The method consisted of evaluating individuals who were reaching with their right hands for five chess pawns, which were placed at varying distances. Specifically, the pawns were evenly spaced in a straight line directly in front of each participant's shoulder. This study focused on a group of 32 participants, which included both males and females. For each participant, low back, elbow and two shoulder angles were collected using a PEAK motion capture 6.0 system. Angles were collected in both the sagittal and transverse planes to gain a 3-D perspective. Data were summarised and correlated against maximum reach arc estimates. Results from the data suggest that both the shoulder and low back are engaged much earlier in a person's reach cycle than previously believed. Specifically, the results show low back engagement (trunk/lumber flexion) as early as 50% of maximum reach with the angle increasing to 5° at around 80% and 10° at 93%, which allows more pronounced forward angular acceleration. This shifts the shape and effective area of a participant's reach arc to a 'dynamic' state and questions if major muscle recruitment in the torso has initiated. The resulting effect is that dynamic and static reach arcs may vary significantly. While this study is too limited to support formal conclusions, these results strongly suggest a need for further investigation into the limits and impact of dynamic reach.

Keywords: dynamic; reach arc; seated; shoulder; back; layout

1. Introduction

This study was developed to understand how and when different muscle groups, and associated joints, engage as seated reaching distances increase. An examination of the literature found several lines of research involving human reach estimates, or arcs. Biman Das of Dalhousie University has been a primary researcher in the area of static reach estimates and their application since the early 1980s, publishing numerous papers (Das and Grady 1983, Das and Behara 1995, 1998, Das and Sengupta 1996, Sengupta and Das 2000, 2004, Kozey and Das 2004). However, research involving the expansion of static reach to dynamic reach estimates is relatively new. Since the late 1990s, work involving dynamic modelling by Zhang and Chaffin at the University of Michigan has produced correlations between joint speed and angle relative to reach location (Zhang and Chaffin 1997, 1999).

The purpose of this research is to investigate the basis, if any, for the integration of dynamic reach into static optimisation equations and models. Previous studies have shown

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various methods of predicting an individual's reach estimate based on anthropometry, as well as its potential applications. This study examined each body segment individually to determine where, when and to what magnitude specific joint engagement occurs. To accomplish this goal, an individual's anthropometry, which provides a pure maximum reach estimate (static), must be modified to account for the individual body segment's dynamic movement that occurs during a reaching task as distances increase from the body. The result gives a time mapping of each joint's involvement level during an ordinary reach, which can be instrumental in understanding the dynamics of reaching.

2. Methodology

The objective of this paper is to examine the relationship between the initiation of major joint movements when reaching to and from a specific point on a horizontal plane. All testing was done from a seated position and based on the participant's static maximum reach estimates as described by Das and Grady (1983) and Das and Sengupta (1996). Simply, static maximum reach estimate can be defined as the maximum distance a person's arm anthropometry allows them to reach without trunk flexion. Testing utilised 32 healthy young adults with no history of shoulder, back or arm injury/dysfunction. All participants tested were students and met the criteria set by Auburn University's Institutional Review Board, #03–205 MR0311. Participant demographic information can be found in Table 1.

Additionally, 27 (84%) of the 32 participants were classified as right-handed with five (16%) listed as left-handed or ambidextrous. Ethnicity was characterised as 80% Caucasian, 13% African-American and 7% other. Anthropometric measurements recorded for participants were based on examples and descriptions found in the 1988 US Army Guidelines (Gordon *et al.* 1989). Measurements taken were:

- acromion-radiale length;
- forearm-hand length;
- hand length;
- interscye I;
- interscye II;
- wrist-wall length, extended.

From these data, all additional anatomical and anthropometric dimensions were derived, allowing for maximum reach arc estimates to be generated for each participant based on Das and Sengupta's (1996) equation. This was then used as a constant to normalise the collected data based on each individual's 100% reach estimate (maximum). This normalisation, in turn, enabled between-subjects analysis, regression and graphing of the collected data.

Table 1. Participant demographics.

Gender	Count	Age (years)		Stature (cm)		Weight (kg)	
		\bar{x}	S	\bar{x}	S	\bar{x}	S
Male	20	21.6	1.0	179.5	6.0	80.8	9.4
Female	12	21.0	1.0	165.0	6.3	70.3	25.4
Pool	32	21.4	1.0	174.1	6.1	76.9	17.1
All	32	21.4	1.0	174.1	9.3	76.9	17.6

The testing apparatus was a kidney-shaped table with adjustable surface height. The table was taped off into a 10 cm grid for analysis and initial setup repeatability. The chair was a standard wood table chair with a fixed back. Colour-coded marks on the floor were used to align the chair and record the distance of the participants and chair from the table. All participants were instructed to achieve neutral posture, i.e. an upright sitting posture (no slumping) with their upper arms hanging vertically down (0° shoulder flexion) extending to their elbow, which were situated at 90° to 100° . Participants' hands were placed comfortably on the table directly in front of their shoulders. Torso positioning was aligned to the centre of the grid table and permitted a maximum of 12 cm clearance between the participant's abdomen and the front of the table. This positioning was intended to allow for participant comfort while reaching for placements beyond maximum reach. For a typical reach study with all movements inside the 100% reach estimates, 2.5 to 5.0 cm would be considered more appropriate (O'Sullivan and Gallwey 2000, 2002).

Five glass chess pawns were selected for transfer. These objects were chosen due to their overall size and weight and the ease with which they could be grasped using the fingers. These pawns were placed at successive grid intersection points (10 cm apart) in a straight line directly in front of the participant's right shoulder, allowing them to be standardised for each trial. Starting from a neutral position, this allowed for a direct reach to each pawn without wrist deviation. The first (nearest) pawn was placed only a few cm from the neutral position of the fingertips, while the fourth and fifth (farthest) pawns were placed at, and beyond, the participant's normal maximum reach estimate. Data were only collected from the first four pawns. The purpose of the fifth pawn was to eliminate any interruption of movement from a participant's anticipation of completing the task. Participants were verbally instructed to start from a neutral position and then, in order from closest to farthest, reach out to grasp each pawn and transfer it to a drop box. The drop box was positioned 15 cm toward the participant and 15 cm to the right of the first pawn, approximately 5 cm to the right of each participant's hand while in the neutral position. Figures 1 and 2 show the table setup from the transverse and sagittal planes, respectively.

After careful consideration, it was determined that four angles would need to be considered to capture the fundamental dynamics of the reach. These included:

- elbow flexion/extension;
- shoulder flexion/extension (accounting for abduction/adduction);
- shoulder flexion/extension;
- trunk/lumbar flexion (i.e. low back angle).

Hand and wrist movements were not collected, but they were controlled to prevent them from confounding the elbow and shoulder. This was accomplished by instructing each participant on exactly how pawns should be picked up or grasped. Figure 3 depicts a visual representation of a person in a neutral sitting posture with each angle displayed.

Data acquisition was done at a sampling rate of 60 frames/s (60 Hz) with a PEAK Performance Motus[®] 6.0 motion capture system (ViconPeak, Centennial, CO, USA). Participant alignment allowed for the XZ-plane to be parallel to the participants' back with the Z-axis being the horizontal control extending perpendicular from the floor. The Y-axis extended perpendicular from the XZ-plane on the same line as the five pawns, with positive values constituting trunk flexion, shoulder protraction, shoulder flexion and

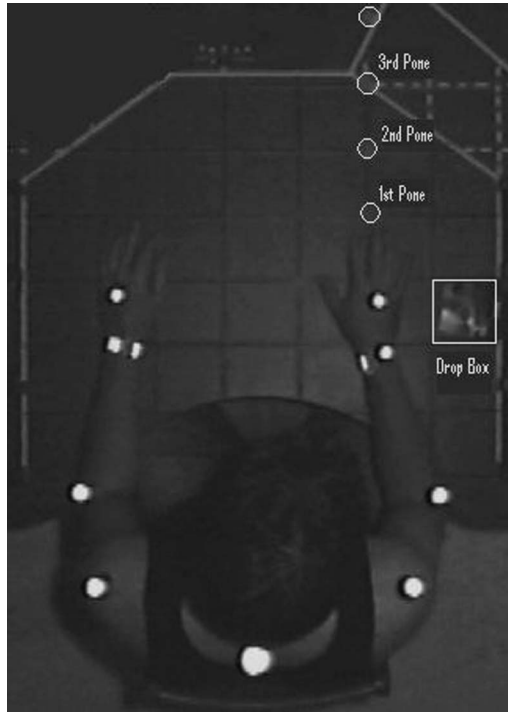


Figure 1. Table setup to neutral participant position (transverse plane).

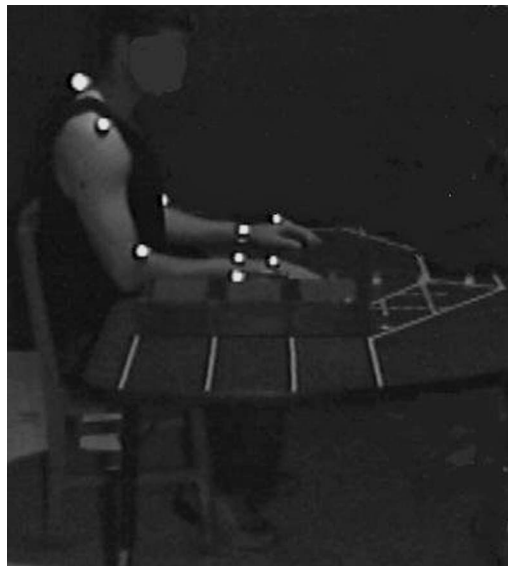


Figure 2. Table setup to neutral participant position (sagittal plane).

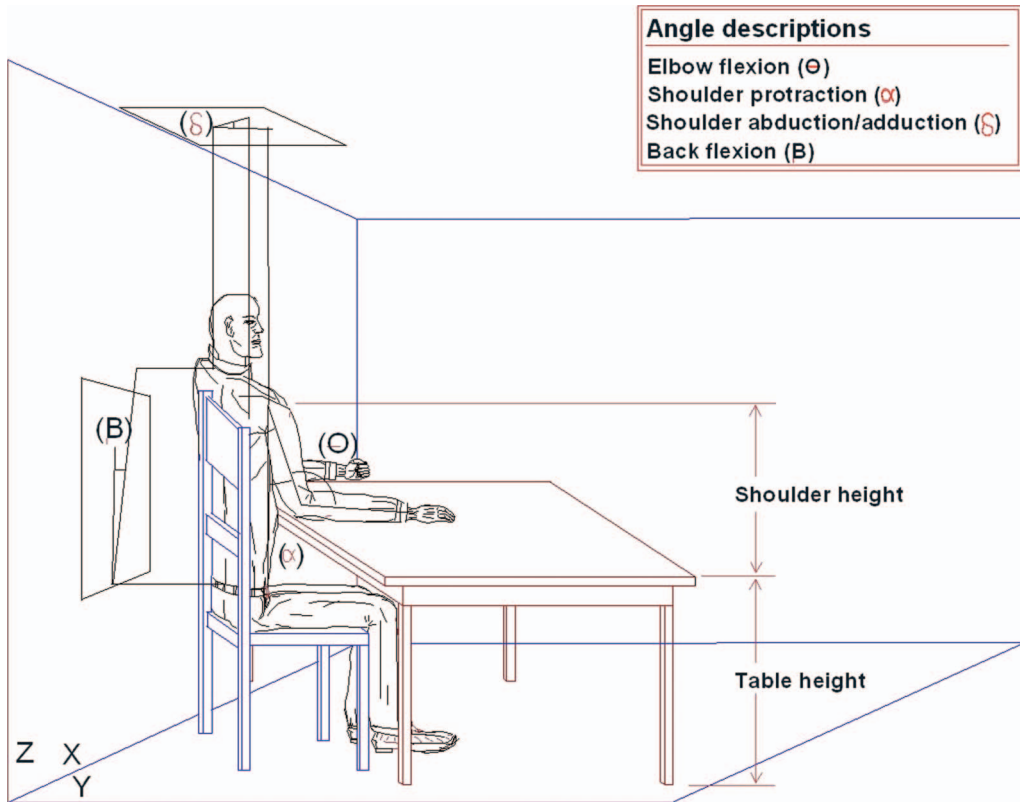


Figure 3. Angles of interest.

elbow extension. Optical marker placements corresponded to: (1 and 2) third metacarpal (middle knuckle, left/right hand); (3 and 4) capitate (left/right wrist); (5 and 6) lateral epicondyle, (left/right elbow); (7 and 8) acromion (left/right shoulder); (9) C7 spinous process (back of the neck). The lumbar back marker (L1) was placed virtually during post-processing due to the chair back obstructing the view of the cameras. This marker was placed using predetermined placement marks for each participant and held stationary from the first frame. While this method does introduce some minor error in the placement of L1, the error would be held constant giving an accurate measurement for the angle of change.

3. Results

A group consisting of 32 participants was evaluated during this pilot study. Two females and one male, all right-handed, were eliminated from the study for not following the testing protocol. Specifically, each eliminated participant began the test in either a reclined or inclined position instead of the neutral position previously described. For the 29 remaining participants, data were analysed using a 100% reach estimate as a basis for normalisation for each of the four angles indicated in Figure 3. The data were examined for both continuous (cumulative) increases over the entire span of the five reaches and

incremental increases in the amount of angular degree shift from pawn to pawn. Incremental increases were determined by comparing only the angular difference from each consecutive pawn's pickup point. Additionally, the data were stratified by gender and examined for differences.

Regression analysis of the continuous data showed that the elbow extension and shoulder flexion curves were correlated both in time and magnitude, as expected, with the only differences being the incremental gain and the overall magnitude. However, the shoulder protraction and the trunk/lumbar flexion showed an unexpected early engagement in the reach cycle, showing a constant rate of positive increase. After careful examination of the data, it was determined that both engaged at approximately 50% of each participant's maximum reach estimation. Additionally, when regression curves were fit to each dataset, the visual results suggested that correlations between all four curves were present when comparing slope termination and cresting points (maxima) to the rate of increasing trunk flexion. To better examine this effect, the absolute value for each data point was used to gain the overall magnitude increase for each successive point. Using this method, elbow extension, shoulder flexion/extension and shoulder protraction appeared to follow a polynomial curve by their linear growth to a plateau cresting point and subsequent decline. Trunk/lumbar flexion appeared to exhibit exponential behaviour by consistently increasing as the other three angles reached plateau and decayed. However, upon examination a third order polynomial turned out to be a better fit. All four regression curves of the continuous raw data were found to have a good fit with R^2 ranging from 0.73 to 0.83, as seen in Figure 4.

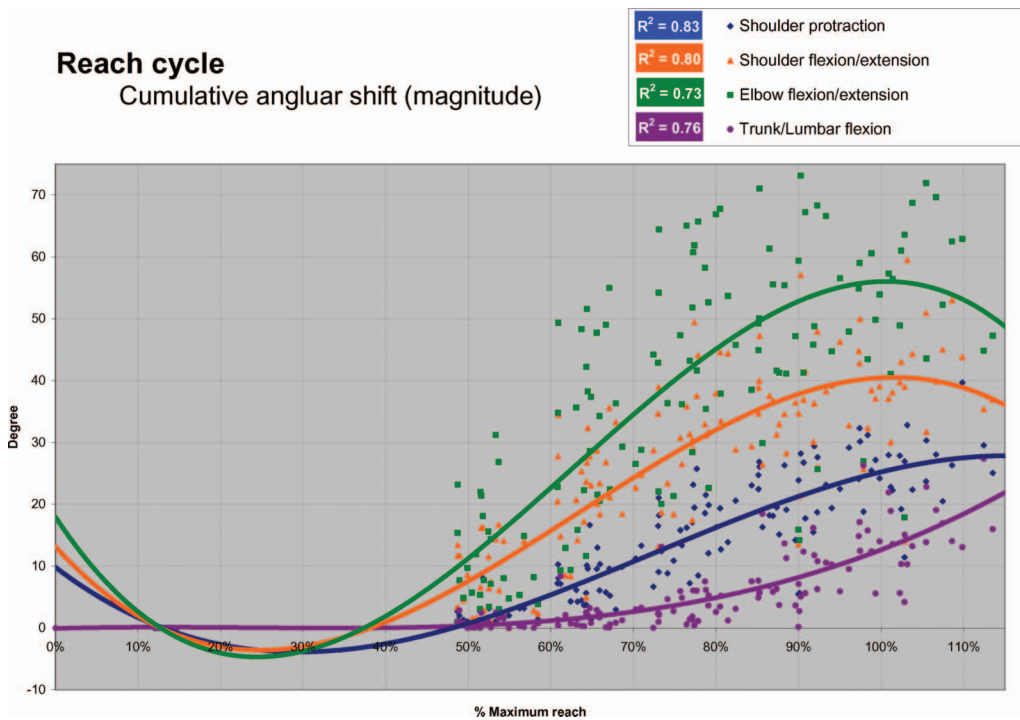


Figure 4. Reach cycle: continuous raw data with corresponding R^2 values.

The regression equations for the curves are:

- elbow flexion/extension: $y = -273.99x^3 + 513.83x^2 - 201.76x + 17.94$;
- shoulder flexion/extension: $y = -194.46x^3 + 368.65x^2 - 146.86x + 13.15$;
- shoulder protraction: $y = -100.52x^3 + 217.90x^2 - 101.96x + 9.83$;
- trunk/lumbar flexion: $y = 29.29x^3 - 20.29x^2 + 3.71x - 0.06$.

The correlations seen in the datasets were examined further by considering the incremental increase of magnitude per 5% increase in maximum reach. The curves shown in Figure 5 do reinforce the suggestion that all four are correlated or related. So to better understand this behaviour, each individual's data and subsequent regression curves were then plotted to find each angle's initiation point, linear slope, crest and decline point. The result was that each angle starting with the earliest initiation point showed a transition of its moment to the next successive curve (joint and segment) until finally being transitioned to the low back (trunk/lumbar flexion). Each major transition of moment is represented by the dotted lines. The moment described here represents the body's natural counterbalancing of weight for the respective extended extremity and torso shift during a reach. For each curve, transition seemed to begin at the end of the linear slope increase and continue to the termination of each joint cycle. Figure 6 is a clearer representation of Figure 5 showing how each stage is transitioned, ultimately placing the total burden of the movement on the lower back (trunk/lumbar extension) at the end of the reaching cycle. Additionally, the rate of angular increase of the torso/lumbar extension was able to be plotted in two stages by rate of increase. The first stage (48–93%) had an increasing rate of $0.00000159 x^{3.2964}$ being continually maintained by major transitions around every 15% of

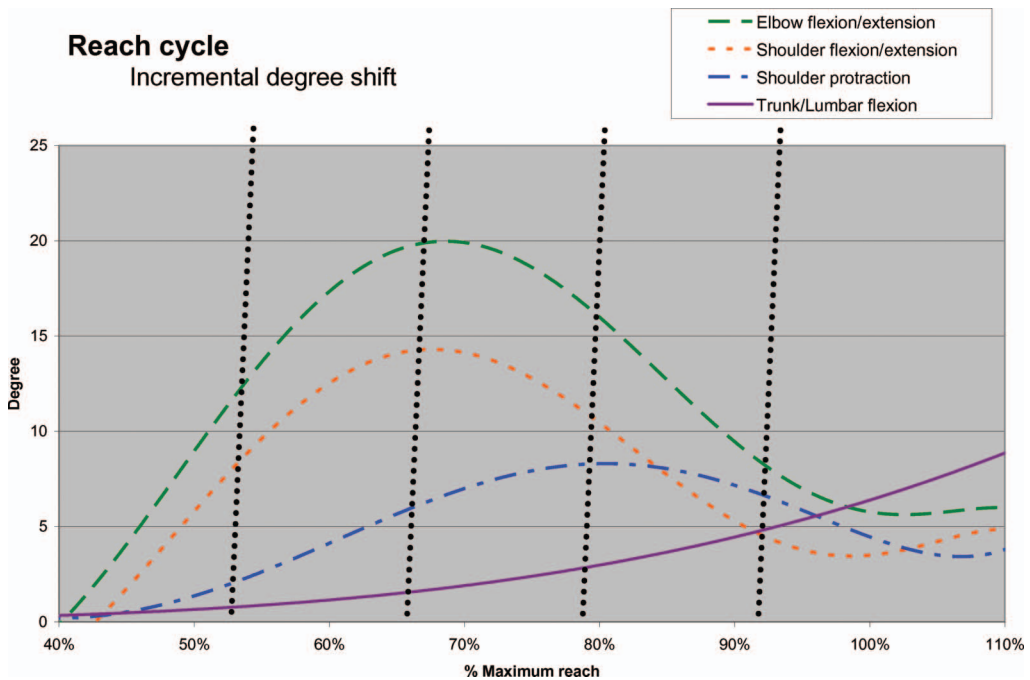


Figure 5. Reach cycle: incremental raw data.

reach. The second stage (94–115%) had an increasing rate of $0.0000008.76 x^{3.4315}$ and is representative of the total load burden of the reach being placed on the low back, due to all other joints being maximised.

Examination of the trunk/lumbar flexion provides a better understanding of the dynamic inactions during a normal reach event. Figure 7 shows a plot of the incremental

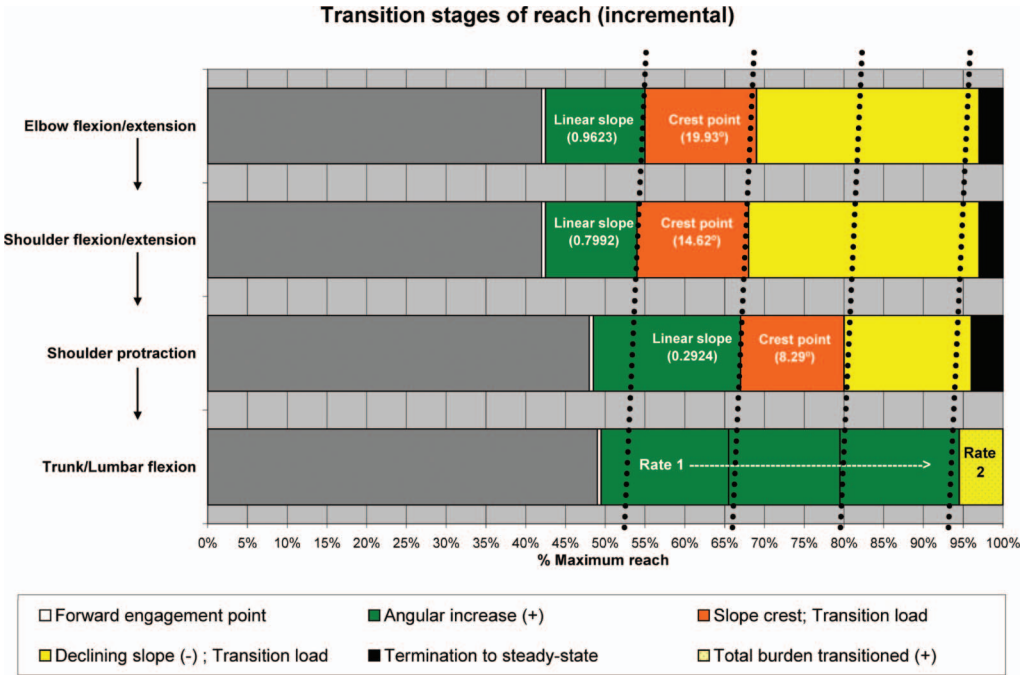


Figure 6. Reach cycle: transition stages (angle and load).

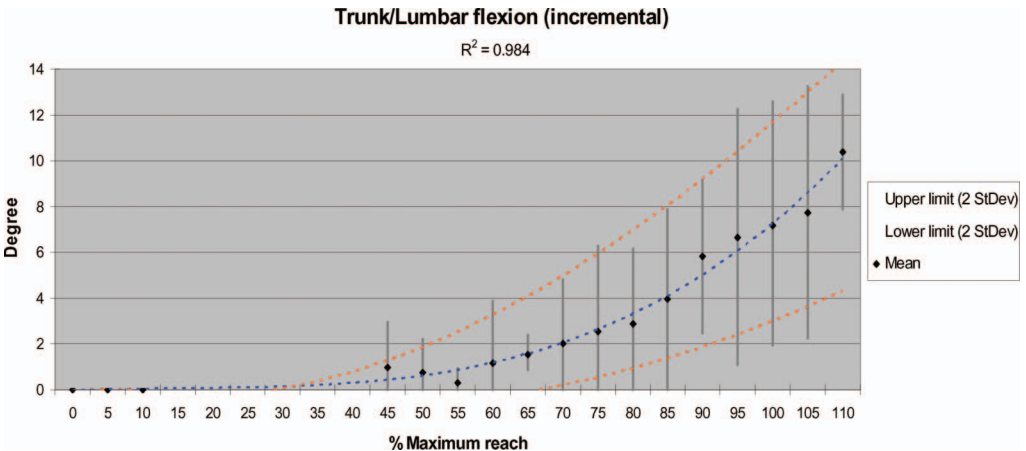


Figure 7. Trunk/lumbar flexion: incremental data with regression curves.

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trunk/lumbar (low back) flexion increase with an upper and lower bound of two standard deviations about the mean. This plot represents the 95th percentile confidence bands of the normal population. Similarly, Figure 8 shows the cumulative magnitude increase in trunk/lumbar (low back) flexion over the same 100% reach estimation (also for the 95th percentile confidence bands for normal population).

The comparison of data from the males and females in the study was of particular interest. Since cumulative examination of the data had shown a transitioning of moment through the successive joints, it seemed likely that male and female regression curves would be similar with slight variation due to the mass and stature differences between the genders. Figure 9 shows a plot of males (dashed lines) vs. females (solid lines) for all four perspective angles of cumulative magnitude. Examination of these regression curves shows a noticeable difference in both initiation point and magnitude. Females engage later in the reach cycle but increase more rapidly to a greater crest point. Males engage earlier and have a less dramatic increase.

To examine this further, the data from each participant were analysed individually using corresponding regression curves and their subsequent initiation point for each angle. Initiation angles were then descriptively analysed and stratified for evaluation using a two sample t-test ($\alpha = 0.05$). Pooling was used whenever the null hypothesis of equality of variance could not be rejected. Results (percent means with each associated variance in parentheses) can be seen in Table 2.

From these data, significant differences were found in the initiation point for shoulder protraction ($t_o = 3.62$, $p = 0.001$) and trunk/lumbar flexion ($t_o = 2.55$, $p = 0.018$). In both cases, males had an earlier engagement point than females. Elbow flexion and shoulder flexion/extension, while different, were not found to be significant.

4. Discussion

The data and figures presented here suggest that there is engagement of low back (trunk/lumbar flexion) when reaching to points within the 100% static reach estimation. For the sample tested, positive engagement is shown to be at 48.98% and 53.35% of maximum estimated reach, for males and females respectively. Incremental analysis shows that the

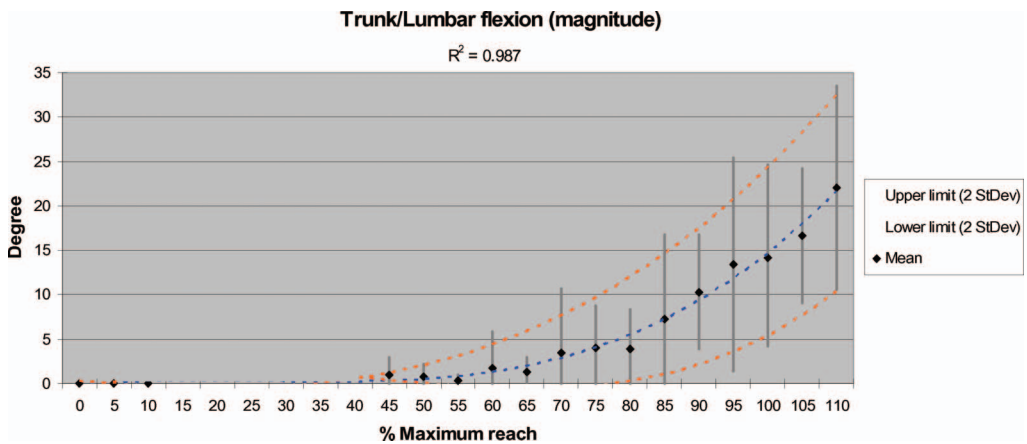


Figure 8. Trunk/lumbar flexion: cumulative data with regression curves.

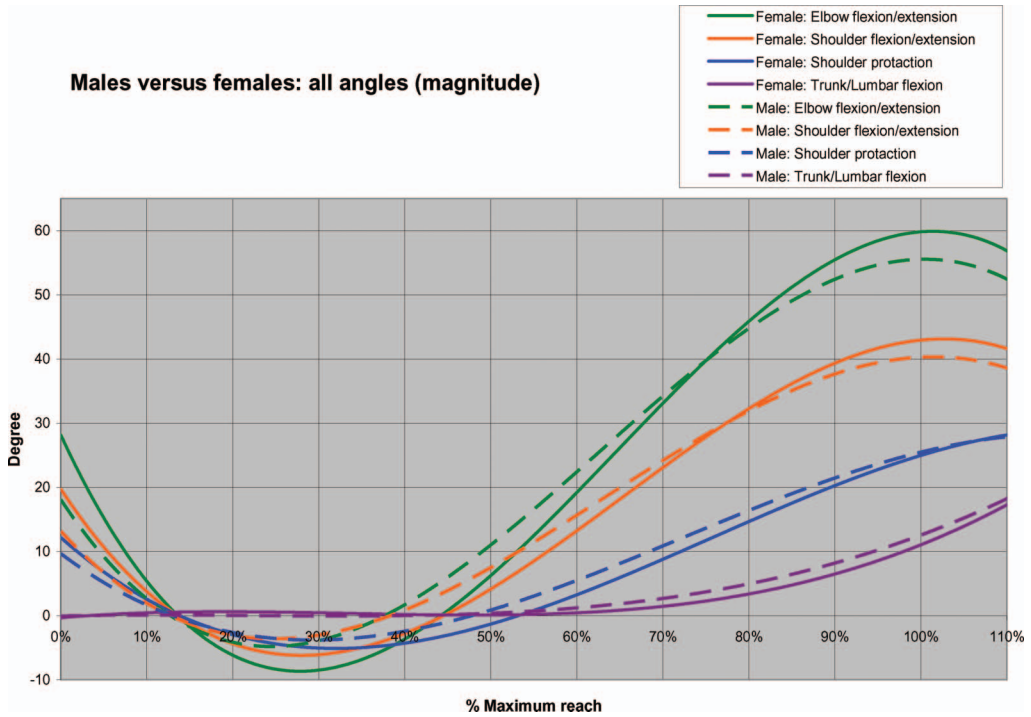


Figure 9. Reach cycle: male vs. female comparison.

Table 2. Forward engagement points.

Gender	Elbow flexion	Shoulder flexion/ extension	Shoulder protraction	Trunk/Lumbar flexion
Male	44.9 (3.0)	43.0 (3.3)	48.6* (0.8)	49.0* (1.6)
Female	46.9 (2.4)	43.6 (6.2)	53.0* (0.8)	53.4* (0.7)
All	45.6 (2.1)	43.2 (3.1)	50.1 (0.7)	50.5 (1.1)

*Significant differences found between males and females.

rate of increase is constant until 93% for each, where the mean degree of trunk/lumbar flexion is 10.7° with an upper and lower limit of 19.4° and 3.0°, respectively. With this rate of increase, trunk/lumbar flexion exceeds 5.0° at around 79% with upper and lower bands of 11.5° and 0.2°. This suggests that half of a normal population would have signification forward angular acceleration at 80% of reach and questions if major muscle recruitment has begun. However, electromyography was not used in this study and estimations as to the level of muscle activity cannot be made. But results do show a change in the shape and effective coverage area for the individual, i.e. a ‘dynamic’ reach arc. Hence, this study ultimately brings into question the use of static reach arc to guide the layout of functional work areas, especially those that will be utilised beyond 80% of maximum estimated reach.

5. Conclusion

The data presented here were part of a study designed to support and better understand where and when the body engaged joint flexion during normal seated reaching activities. Currently, most functional work layouts are based on the use of maximum estimated static reach. However, the present data suggest that an individual's 'dynamic' reach arc has a different shape and covers a different effective area than the static reach arc. Although this study was unidirectional, and therefore provides an incomplete mapping of the entire pattern/area, it does suggest a strong need for a deeper understanding of dynamic reach.

Possible directions for future research in this area could include:

- (1) the mapping of a complete seated 'dynamic reach arc' for both genders with special emphasis being placed on shoulder dynamics relative to back flexion;
- (2) the mapping of a dynamic reach arc using weighted items for investigation of further manipulation.

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