Development of a Kinematic Hand Model for Study and Design of Hose Installation

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Abstract. Kinematic hand models can be used to predict where workers will place their fingers on work objects and the space required by the hand. Hand postures can be used to predict hand strength. Kinematic models also can be used to predict tissue stresses and to study work-related musculoskeletal disorders. Study and design of manual hose installation is an important application for kinematic hand models. Hoses are widely used in many mechanical systems such as autos, aircraft and home appliance, which are all mass-produced on assembly lines. Studies of automobile assembly jobs show that hose installations are one of the most physically demanding jobs that workers perform. Hoses are a good starting point for kinematic model development because they can be characterized as simple cylinders.

Keywords: Hands, kinematic model, manufacturing.

1 Introduction

Manual work continues to be a vital part of our industrial economy. People have many advantages over machines: they are able to compensate for subtle material and process variations; they can quickly learn to perform different jobs in an agile production process; and they don't require huge upfront capital investments. However, people, like machines, have operating limits and constraints. Job demands must not exceed their strength capacity and sufficient space must be provided to reach for and grasp work objects.

Production hose installation is an example of a job that is routinely performed by hand. The external size and shape of hoses often varies slightly from one hose to another. Hoses are often jointed to a flange in confined and obstructed workspaces. Studies by Ebersole and Armstrong [1 and 2] showed that manual hose installation is one of the most demanding auto assembly jobs that workers perform. Static anthropometric data, such as hand length, width and thickness cannot be applied directly to determine if there is sufficient room for the hand. Static anthropometric data, however, can be used with kinematic models to predict possible grip postures and how much space will be occupied by the hand in those postures. Additionally posture can be used to be used to predict hand strength [3]. Kinematic models also can be used to estimate tendon excursions and loads associated with reaching and grasping and to study risk of musculoskeletal disorders in the wrist [4].

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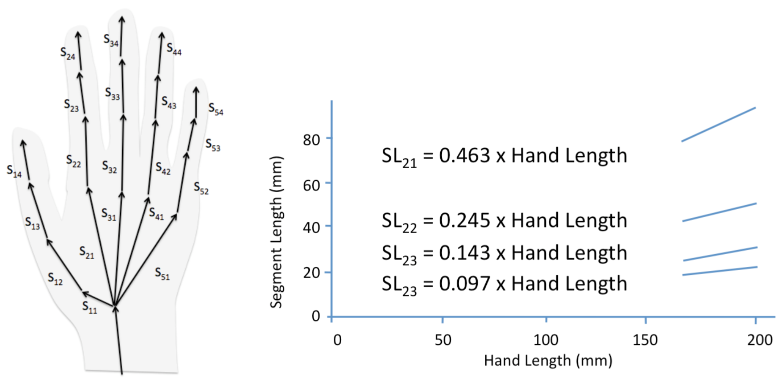
This paper describes the development of a kinematic model for studying and designing manual hose installation tasks. Although the main focus of this work was on hoses, the resulting model has potential applications to tasks that involve gripping of other parts and tools.

2 Methodology

2.1 The Link System

The link system used for development of this model was based on that developed by Buchholz, et al. [5]. They studied the relationship between segment lengths and hand lengths. Planner radiographs were obtained for series of joint angles from straight to fully flexed. Reuleaux's method was used to determine the joint centers. Segment lengths were then computed as the distances between successive joint centers. Segment lengths were found to be highly correlated with hand lengths. Figure 1 shows segments and the coefficients used for computing their length.



	Digit				
Segment	1	2	3	4	5
1	0.118	0.463	0.446	0.421	0.414
2	0.251	0.245	0.266	0.244	0.204
3	0.196	0.143	0.170	0.165	0.117
4	0.158	0.097	0.108	0.107	0.093

Fig. 1. Relative link lengths from Buchholz, Armstrong, Goldstein [5]

2.2 Hand and Object Surfaces

Buchholz and Armstrong [6] in 1992 proposed a series of ellipsoids that were scaled on segment lengths, widths and thicknesses to give the model hand shape. Use of geometric objects made it possible to detect contact among hand segments and external objects in a virtual environment. Model manipulations were quite slow on

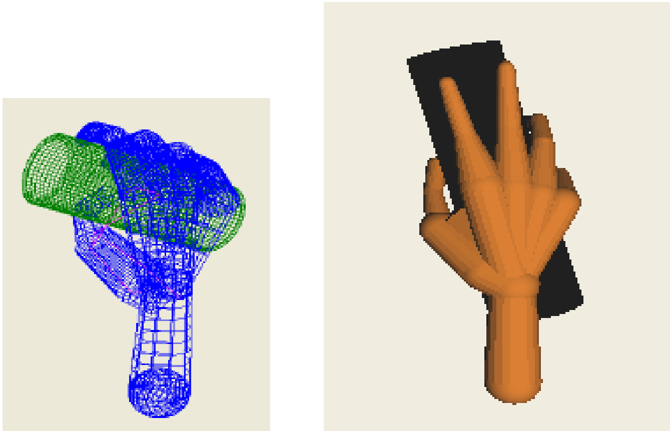


Fig. 2. Choi and Armstrong (7) used arrays of points based on hand segment sizes and truncated cones to depict hand surfaces (left). The surfaces filled in using Open GL (right).

computers at that time. Recently Choi and Armstrong [7] utilized arrays of equally spaced points based on segment sizes and truncated cones to depict hand surfaces (see Fig. 2).

2.3 The Graphical User Interface and Manipulation of Model

A graphical user interface was designed to facilitate manipulation of the model (see Fig. 3). The program will compute segment sizes for a given percentile hand length using the Buchholz coefficients or the user can specify desired hand sizes. The program also provides a selection of standard object shapes that can be scaled to desired sizes in each of the three dimensions. The user can also place the object at desired locations and orientations. For example, a hose would be represented as a cylinder and could be placed at a right angle to the hand, parallel to the hand, or something in between. The user also has the option of entering other objects as arrays of surface points.

The joint angles can be manipulated manually by entering angles. Positioning the fingers on a work surface is a tedious process and the results will vary from one user to another. Still, it is possible to get an idea of how well an object fits the hand, where the fingers might touch the work object and what kinds of postures are possible.

It is helpful if the user has some familiarity with what the worker is trying to do. Grieshaber and Armstrong [3] studied the postures that workers used to install hoses in 113 hose installation tasks in twenty-eight auto assembly tasks. They found that workers are more likely to use a power grip than a pinch grip posture as the ratio of hose diameter to hand length increased and the hose insertion forces increased (see Fig. 4). Some workers still use a power grip posture for small hoses and low forces and some use a pinch grip for large hoses and high forces. Other investigators have studied how people grasp objects with the goal of developing a set of primitives for robots [8]. These primitives also provide a guidance manual for manipulation of

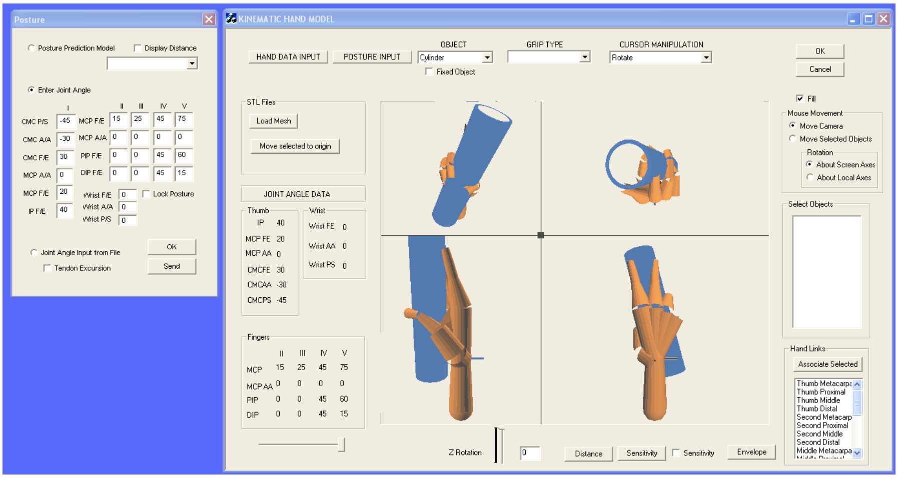


Fig. 3. Graphical user interface used by Choi and Armstrong [7] to manipulate Kinematic Hand Model

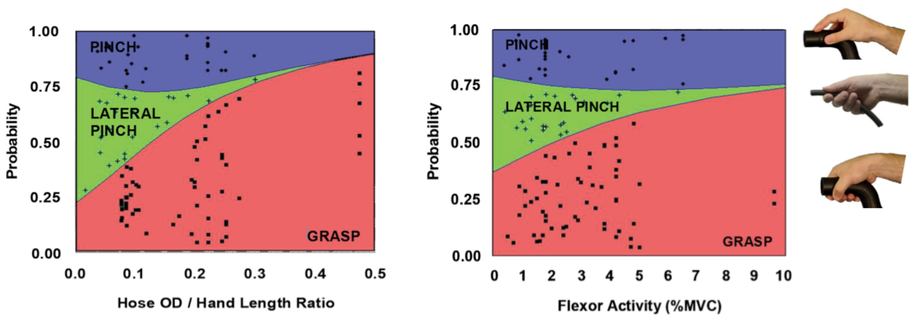


Fig. 4. Hand posture versus hose OD/ hand length ratio (left) and finger flexor activity (normalized 0-10) (right)

kinematic models. Grip postures are no doubt affected by other factors, such as access to the flange and the worker's behavior.

Although kinematic models do not force objects, that does not mean that the users of those models cannot. It must be possible for the hand to achieve a static equilibrium with the grip objects, that is:

$$\sum \vec{F}_i = 0 \text{ and } \sum \vec{M}_i = 0. \qquad (1)$$

This means that if the fingers press on one side of an object and that object is not constrained externally, e.g., work surface railing, etc., then that object must be supported on the opposite side by the thumb or the palm. Skin deformation and friction will help keep objects from slipping out of the hand if the fingers are not exactly aligned on opposite sides of the grip object.

2.4 Posture Prediction Algorithms

Some of the work required to manually position the fingers on the surface of a work object can be reduced through the use of posture prediction algorithms. These algorithms either flex the fingers until contact is detected between segments of the fingers and the grip object, or alternatively, they use optimization methods to calculate the best fit between the hand and work object. Buchholz [6] adapted an algorithm from Fleck and Butler [9] to detect contact between ellipsoid representation of the finger segments and the geometric representation of the grip object. The user first specified the geometry of the grip object and its location and orientation with respect to the hand. The posture prediction routine then started with the fist knuckle and rotated that joint until contact occurred between the hand and the work object. The process was then repeated for the second and then the third knuckles. Buchholz reported very good agreement between predicted and observed postures for gripping different sized cylinders perpendicular to the long axis of the hand using a power grip. The need to represent grip objects mathematically, the lack of a graphical user interface, and the slow processors at that time restricted the use of the resulting model.

Choi and Armstrong [7] utilized a contact algorithm that computed distances between points representing surfaces of the hand and surfaces of the work object. Although this is computationally intensive, it is within the capacity of most modern desktop computers. A number of studies were performed to evaluate the sensitivity of posture to hand size, skin deformation and cylinder diameter. The contact algorithm made it possible to simulate skin deformation by allowing penetration of the object into the hand (negative object hand distances). Model predictions explained 72% of the observed hand posture variance (R^2) for gripping cylinders with diameters between 26 and 114.3 mm. Prediction errors ranged from -16.4° to 18.7°. The model tended to overestimate the third knuckle angles for cylinder sizes (-16.4° ~ -0.4°) and to underestimate first knuckle angles for all cylinder sizes (-2.4° ~ 18.7°). Cylinder size had the most profound effect on finger joint angles. Hand length and width (from small female to large male percentiles) and skin deformation (up to 20% penetration) had only a small effect on joint angle predictions.

Subsequent studies examined how predicted joint angles are affected by where the object is placed in the hand and how it is oriented [10]. Hand placement is important especially when posture prediction algorithms are used. If the object is place too close to the wrist, it is possible for the fingers to completely miss the object as the fist closes. If it is placed too close to the fingertips, the hand may not close much at all before contact occurs. Posture predictions were generally pretty consistent as long as they were between the middle of the palm and the first knuckle. Studies of grip behavior, [3; 8; 11; 12], can be used to guide finger placement and determine if the resulting grip postures are feasible.

Lee and Zhang [13] proposed an optimization model based on the assumption that the best prehensile configuration of the hand in power grip optimally conforms to the shape of the grip object. Their model simultaneously minimized the distances between joint centers and the surface of the grip object. Their model was tested by comparing predicted and observed postures of twenty subjects gripping vertically oriented cylindrical handles 45 and 50 mm in diameter. Average root mean prediction errors across all conditions were less than 14 degrees. This optimization routine can be extended to other grip objects, but reformulation of the model would be required if the hand is not in continuous contact with the grip object. The advantage of this model is that it does not require iterations to find the final posture. The disadvantage is that it may have to be reprogrammed for application to grip objects with other shapes or other hand postures. Also, it does not allow the user to easily explore subtle variations in object placement and orientation or finger placements.

2.5 Finger Movements

Posture predictions are affected by rotation rates of the finger joints. Figure 5 shows the finger tip trajectories based on rotating one joint at a time versus rotating them together at the same rate. It can be seen that rotating them together reduces the reach area of the fingertip. As a practical matter, people don't close their fist one joint at a time. Neither do they close them at the same rate. Kamper, et al. [14] studied finger motions for 10 subjects grasping different objects. They observed that the average rate of rotation for the second knuckle was only 26 to 72% that of the first knuckle and that the rate for the third knuckle was only 16 to 36% that of the second knuckle. There were significant variations among fingers and subjects. The actual finger trajectory will probably be somewhere between the two extremes shown in Fig. 5.

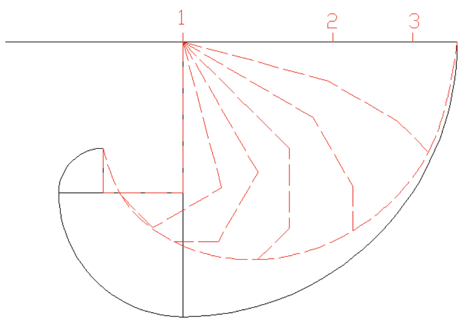


Fig. 5. Fingertip trajectories based on rotating joint 1 to its maximum, then joint 2, then joint 3 (solid lines) and based on joints 1, 2 and 3 together at the same rate

One of the challenges to developing accurate finger motions models is that the finger motions are usually combined with movement of the hand towards the work object and starts with opening the hand so that the grip object can pass between the thumb and the fingers [15; 16]. Figure 6 shows hand trajectory and wrist and index finger angles for an average of six subjects reaching for a vertical cylinder. Starting from a relaxed posture (25° Extension and 45°, 30° and 10° Flexion) the wrist extends and the hand opens (Δθ = +8°, -22°, -12° and -5°) before closing (Δθ = +7°, +11°, +10° and +10°). It also can be seen that the trajectory of the wrist is curved. It has been shown that how much the hand opens and how much it closes are related to the

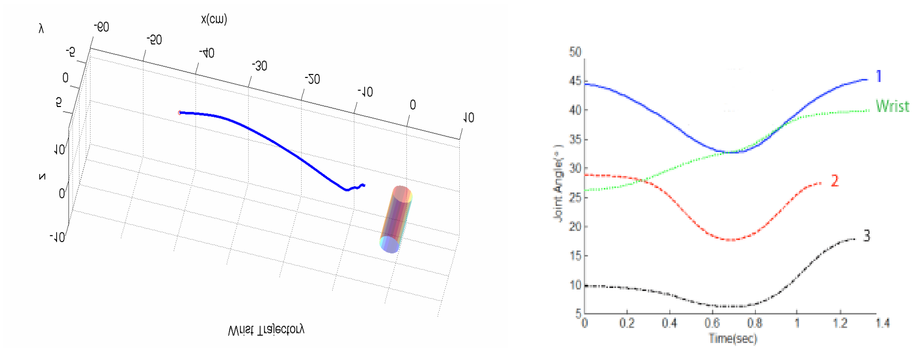


Fig. 6. Wrist trajectory (left) and the first (1), second (2) and third (3) knuckle angles of the index finger and wrist angle (right) for a 40 cm reach to grasp a 15 cm diameter cylinder

size of the object [15; 17; 18; 16; 7]. Models are needed that describe the finger motions as functions of time so that they can be used with kinematic models.

2.6 Required Hand Space

3-D kinematic hand models can be used to predict the hand space requirement for hose placement tasks (see Fig. 7). Hand space requirements were simulated using a 3-D kinematic hand model described by Choi, et al. [19] and compared with experimental data reported by Grieshaber and Armstrong [20]. The simulation results showed good agreement with measured data with an average 17% underestimation of hand space envelopes. Simulations showed that pinch grip required an average of 72% larger space than power grip, the rotation method required an average of 26% larger space than the straight method, and a 95% male hand size required an average of 44% larger space than 5% female hand length. The hand space envelope can give useful information to designers and engineers who design workspace and parts to avoid problems of obstruction. Future work will include the addition of modules to the kinematic model interface for capturing hand space data and validating space predictions for a range of different size and shape grip objects.

2.7 Work-Related Musculoskeletal Disorders

Another important use of kinematic models is evaluating risk of work related musculoskeletal disorders. Choi and Armstrong [21] conducted a study to examine the relationship between tendon excursion and wrist movements and MSDs (musculoskeletal disorders) of the hand and wrist. Video tapes were obtained from a previous study by Latko, et al. [22] that showed a strong basis between Hand Activity Level and risk of non-specific hand pain, tendonitis and carpal tunnel syndrome. One medium-risk job and two low-risk jobs were selected from an office furniture manufacturing facility. Two high-risk jobs, one medium-risk job, and one low-risk job were selected from a manufacturing site for industrial containers. Two high-risk jobs and one medium-risk job were chosen from a company manufacturing spark plugs. Time-based analyses were performed for the right hand and the wrist as described by Armstrong, et al. [23].

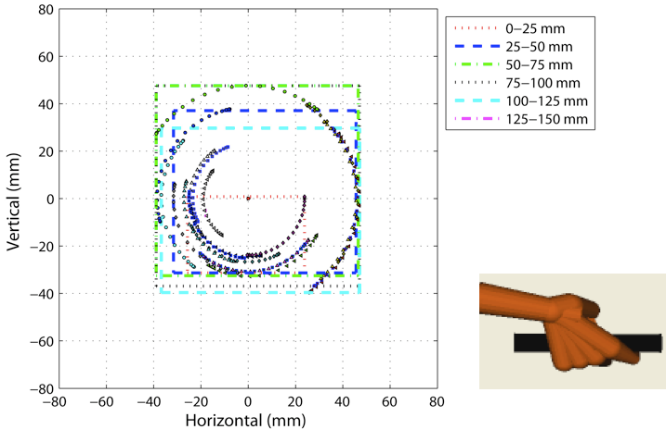


Fig. 7. Space occupied by the hand while inserting a hose using predicted using moments

Tendon excursions of FDP (flexor digitorum profundus) and FDS (flexor digitorum superficialis), projected for one hour, were assessed by using the models developed by Armstrong and Chaffin [24]. Cumulative tendon excursions were computed from angular velocities and peak wrist excursions. First, wrist posture as a function of time, θ(t), can be written as

$$\theta(t)=\sum \theta_{0i}\sin(\omega_i t+\Phi) \ , \tag{2}$$

where θ_{0i} is peak wrist excursion, ω_i is the frequency, Φ is the phase, and t is time. Second, angular velocity, θ'(t), can be calculated as

$$\theta'(t)=\sum \theta_{0i}\omega_i\cos(\omega_i t+\Phi) \ . \tag{3}$$

Third, the cumulative tendon excursion is;

$$\int_0^T \left| r\,\dot{\theta}(t) \right| dt = \int_0^T \left| \sum r\theta_{o\,i}\omega_i \cos(\omega_i t+\phi) \right| dt \tag{4}$$

Where r is the radius of tendon curvature in the wrist, θ' is the angular velocity of the wrist, and T is work duration of observations. It can be seen that total tendon travel during the work period provides an exposure index that captures frequency, ω_i, peak wrist excursion, θ_{0i}, and work duration, T. Mean velocity and acceleration for wrist flexion-extension and cumulative tendon excursions were significant ($p<0.05$) across risk groups, and these values corresponded to the risk of MSDs. In future studies we will add excursions due to finger motions in addition to wrist motions and add tendon force to the analysis. Kinematic models can be used to study wrist finger and tendon motions.

3 Conclusions

Kinematic models can be used to determine how workers may grasp different work objects, how much space is required for their hand, and the required tendon forces and hand strength. Contact and posture prediction algorithms facilitate use of kinematic models, focus on one best grip and do not automatically capture the variations that may occur among different workers. Many of the studies heretofore focused on grasping cylinders. These studies are particularly relevant to hose installation. Future studies will focus on enhancing models for grasping irregular shape objects, development of models for describing hand and finger motions, risk of musculoskeletal disorders, improving the graphical user interfaces, and integration of models into CAD environments.

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