

# Applying Empirical Data on Upper Torso Movement to Real-time Collision-free Reach Tasks

Liming Zhao, Ying Liu, Norman I. Badler  
Center for Human Modeling and Simulation  
Computer and Information Science  
University of Pennsylvania

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## ABSTRACT

Simulating human reach is still challenging when considering complex interactions with the environment. Standard approaches involve inverse kinematics (IK) methods and usually require a complete but exponential cost search in configuration space. In ergonomic applications, both "naturalness" and interactive performance are important. We describe a real-time, collision-free, sternum-rooted IK solution for an articulated human figure based on motion capture data, human strength models, and multi-joint coordination functions. Movement paths are discovered through spatial search in a partitioned workspace. The system generates natural collision-free reach motions in real-time. The resulting animations and statistics demonstrate the efficacy of this approach.

## INTRODUCTION

A fundamental capability for a virtual human model is being able to reach naturally to a given position in space. There are two major approaches to solving this reach planning problem and motion planning problem in general: model-based and data-driven.

Most of the planners developed in robotics are model-based as they restrict the search space by kinematic, dynamic or biomechanical models to generate motions for a virtual character. This approach provides a compact and flexible representation of human motions and it can generate motions in a continuous domain with both internal (joint limit) and external (obstacle) constraints. In general, to guarantee a solution, if one exists, a model has to search over a configuration space that grows exponentially with the number of degrees of freedom (DOF). In addition, standard model-based approaches have no naturalness constraints on the motions they produce.

The data-driven approach utilizes motion capture devices to build a database of human postures. Later, an arbitrary motion is generated using some or all the postures in the database [15,16]. Since the approach

works directly with captured postures, the resulted motions are natural and exact. However, methods to adapt existing postures to a new posture are not simple and are limited to the data collected and to the specific person that has been captured. Improvements have been attempted by modeling the segment angles with functional regression analysis from the motion database and by building models to interpolate new postures among existing ones [4,17].

The system presented in this paper takes advantage of both the model-based and data-driven approach for reach planning. It builds a model that can generate continuous configurations and also incorporates naturalness constraints by encoding strength into the multi-joint functions that correlate movements across different human joints. Such functions have been extracted by regression analysis on empirical data from motion capture. They not only ensure the naturalness of the configurations generated, but also reduce the number of DOF in the search space. The demonstration shows the efficacy of this approach and its suitability for VR avatars, animation posing, or ergonomics analysis applications

## REACH PLANNING SYSTEM

The exposition of our method is organized as follows. The Human Strength Model section explains how strength is evaluated and encoded into the configuration search procedure and how multi-joint functions are extracted to reduce the search complexity. The Strength-based Reach Planning section describes the system and its components in detail.

## HUMAN STRENGTH MODEL

Human strength is important to human performance. It is defined as the maximal force that a muscle (group) can exert in a single voluntary effort under prescribed conditions [12,13]. While human strength can be affected by many parameters such as age, gender, body position, handedness, etc. [2,6], orientations of each body segment are the principal determiners of strength.

The quantitative relationship between joint angles and strength exertion capabilities in our system is depicted using strength curves based on Mital and Pandya's work for shoulder strength in terms of abduction/adduction angles [11] and flexion/extension angles [14]. These curves agree with our intuition that shoulder strength is near minimum at the end points of the range of the motion (joint limits) and maximum at the region around zero degree angle (neutral position).

According to the data, shoulder strength is modeled as a function of joint angles using regression analysis. The approximated strength function for shoulder abduction/adduction and flexion/extension movements in terms of horizontal ( $\alpha$ ) and vertical ( $\beta$ ) shoulder rotations are represented as  $S_H(\alpha)$  and  $S_V(\beta)$  respectively:

$$S_H(\alpha) = \begin{cases} 65 + 0.33 \times \alpha & \text{if } -60^\circ \leq \alpha < 0^\circ \\ 65 - 0.23 \times \alpha & \text{if } 0^\circ \leq \alpha \leq 90^\circ \\ 54 - 0.11 \times \alpha & \text{if } 90^\circ < \alpha \leq 180^\circ \end{cases}$$

$$S_V(\beta) = \begin{cases} 56.666 + 0.793 \times \beta & \text{if } -60^\circ \leq \beta < -30^\circ \\ 65.752 + 1.096 \times \beta & \text{if } -30^\circ \leq \beta < 0^\circ \\ 65.752 - 0.51383 \times \beta + 1.1058 \times 10^{-3} \times \beta^2 & \text{if } 0^\circ \leq \beta \leq 180^\circ \end{cases}$$

Evaluating the strength of abduction/adduction and flexion/extension together is a multi-pass process. Different strategies are used in different passes.

#### 1. First level criterion – preferred strength level

Humans prefer movements where joint poses tend toward regions exceeding a preferred strength level so that they can operate without incurring significant discomfort [5]. Represent the two preferred strength levels for shoulder abduction/adduction ( $\alpha$ ) and flexion/extension ( $\beta$ ) as  $SL_H$  and  $SL_V$ . Let the two strength functions corresponding to the two movements be  $S_H(\alpha)$  and  $S_V(\beta)$ , which are calculated using formulae described in above. The strategy can be represented by the following functions:

$$f_H(\alpha) = \begin{cases} 0 & \text{if } S_H(\alpha) \geq SL_H \\ 1 & \text{otherwise} \end{cases} \quad f_V(\beta) = \begin{cases} 0 & \text{if } S_V(\beta) \geq SL_V \\ 1 & \text{otherwise} \end{cases}$$

$$f_R(\alpha, \beta, \gamma) = f_H(\alpha) + f_V(\beta)$$

The smaller the value of  $f_R(\alpha, \beta, \gamma)$  is, the more strength the arm can exert, and the more preferable the movement.

#### 2. Second level criterion – maintaining the strength level

Based on the value of  $f_R(\alpha, \beta, \gamma)$ , potential configurations for the arm fall into three categories listed below. Different strategies are applied to different categories.

- $f_R(\alpha, \beta, \gamma) = 0$

When  $f_R(\alpha, \beta, \gamma) = 0$ , strength is not the major concern. Instead, the movement that requires the least exertion is favored. Exertion needed to perform a movement is defined as the displacements of the joint angles from

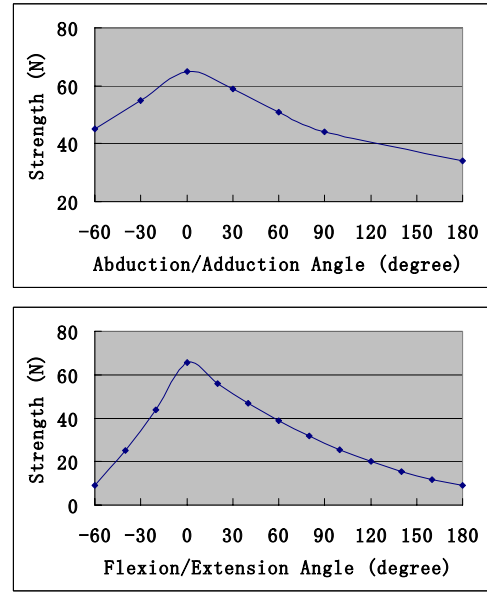


Figure 1. Approximated strength curve in terms of shoulder angle.

their initial to final posture. Shoulder exertion is represented as follows:

$$f_E(\alpha, \beta, \gamma) = \omega_\alpha |\alpha - \alpha'| + \omega_\beta |\beta - \beta'| + \omega_\gamma |\gamma - \gamma'|$$

where  $(\alpha', \beta', \gamma')$  and  $(\alpha, \beta, \gamma)$  represents the shoulder rotation angles at the initial and final posture, respectively, and  $\omega_\alpha, \omega_\beta, \omega_\gamma$  are weights set to reflect the differences existing in muscles that are responsible for movements at each DOF. With the same amount of angular displacement, more exertion will be needed for weak muscles than for strong muscles.

- $f_R(\alpha, \beta, \gamma) = 1$

This happens when either  $f_H(\alpha) = 1$  or  $f_V(\beta) = 1$  for a given  $(\alpha, \beta, \gamma)$ . In this case, the preferred solution is a movement that results in the most strength increase. This strategy is represented as the following function:

$$f_S(\alpha, \beta, \gamma) = \begin{cases} \frac{SL_H - S_H(\alpha)}{SL_H - S_H^{\min}} & \text{if } f_H(\alpha) = 1 \\ \frac{SL_V - S_V(\beta)}{SL_V - S_V^{\min}} & \text{if } f_V(\beta) = 1 \end{cases}$$

where  $S_H^{\min}, S_V^{\min}$  are the minimum abduction/adduction and flexion/extension strength respectively. The smaller the value of  $f_S(\alpha, \beta, \gamma)$ , the more preferred the movement.

- $f_R(\alpha, \beta, \gamma) = 2$

This occurs when both the horizontal and the vertical strengths fall below the preferred comfortable strength levels. When this is the case, movement is encouraged when it results in a configuration for the arm where more strength is possessed. This can be represented as:

$$f_S(\alpha) = \frac{SL_H - S_H(\alpha)}{SL_H - S_H^{\min}}, \quad f_S(\beta) = \frac{SL_V - S_V(\beta)}{SL_V - S_V^{\min}}$$

$$f_T(\alpha, \beta, \gamma) = f_S(\alpha) + f_S(\beta) - f_S(\alpha) \cdot f_S(\beta)$$

The term  $f_S(\alpha) \cdot f_S(\beta)$  is used to favor the movement that distributes the strength changes evenly in both of the two directions. The smaller the value of  $f_T(\alpha, \beta, \gamma)$ , the more desirable the movement.

### 3. Third level criterion – preferred side

An algorithm (Algorithm 1) to decide elbow pose is constructed to impose inward/outward rotation constraints for the shoulder. For the right (left) arm, more natural postures can be generated by positioning the elbow to the right (left) side of the plane determined by the human’s waist, shoulder and wrist. This helps reduce the elbow search space while producing natural postures.

With the strength model, every arm configuration can be associated with a strength quantity according to shoulder rotation angles and the elbow pose. Therefore, from all potential arm configurations, we can easily select those natural configurations with shoulder strength above a threshold and order them according to their strength.

For the body rotation, many studies have shown that a body segment will only be moved if a target cannot be reached by all segments located more distally and its rotation is involved only when reaching sideward more than a certain degree [1,8]. Experiments also show that the starting rotation degree varies according to the target distance. Through regression analysis, significant linear relationships have been found between reach direction and rotation of chest and pelvis (figure 2) [3]. Table 1 illustrates the chest rotation vs. arm reach direction by linear regression on motion capture data [3]. Note that the joint recruitments are phased; they do not all change simultaneously. By applying Table 1 during reaching, body rotation can be read from the multi-joint function. Shoulder position at that time is the initial shoulder position applied by a rotation transformation of body rotation angle around the vertical axis. This procedure can be viewed as dimensionality reduction since it correlates the shoulder with wrist in terms of a multi-joint function to reduce the number of search space unknowns.

Notice that static strength data are used in this human strength model. Strength will vary for highly dynamical motions. However, most reach motions we are interested in for ergonomics are low velocity movements which are dominated by static strength. In addition, such static strength data are easy to measure [3,11,14].

## STRENGTH-BASED REACH PLANNING

The reach planning problem that we focus on is defined as follows: in a complex 3D workspace, given a starting configuration and a target position of the end-effector, compute a collision-free motion path that an articulated human arm can follow, involving body rotation if necessary, to reach from start pose to target end-effector position automatically. Note that a valid end pose is *not* required, as the reach may indeed fail.

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### Algorithm 1: RightArmSide(Wrist $\bar{w}$ , Elbow $\bar{e}$ , Shoulder $\bar{s}$ , Waist $\bar{a}$ )

---

```

{
  //Get normal vector of plane P consists of wrist, shoulder and waist.
   $\bar{n} = \text{normalize}[(\bar{s} - \bar{w}) \times (\bar{a} - \bar{s})]$ ;
  //  $\bar{e}_p$  is the projection of  $\bar{e}$  on the plane P.
   $\bar{p} = \text{normalize}[(\bar{e} - \bar{e}_p)]$ ;
  if ( $\bar{n} == \bar{p}$ ) then
    return RIGHT;
  else
    return LEFT;
}

```

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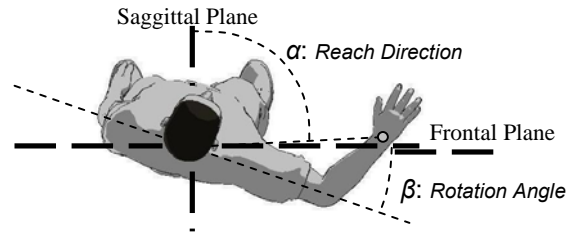


Figure 2: Reach Direction and Body Rotation angles.

Reach distance	Slope	Intercept	Starting Angle
75cm	0.50	-26.7	53°
85cm	0.45	-18.9	42°

Table 1:  $Chest\ rotation = Reach\ direction \times Slope + Intercepts$

Assume the wrist is the end-effector, the position of the palm center is just a further search for a point on a sphere. Reach planning can be viewed as finding a path for the end-effector which connects the starting and target position, such that for every node on the path, there exists at least one arm posture (which is displayed and recorded) that is within motion smoothness, human strength, and collision-free constraints.

We divide this reach planning system into two modules: The Strength-based Configuration Generation Module takes a 3D position as input and outputs a valid arm configuration with wrist at this position. Such a configuration must satisfy the strength, motion smoothness, and collision-free constraints. The Guided Path Planning Module extracts guiding nodes from start and target position to ensure a high-level shortest path and performs a best first search for the next end-effector position between two guiding nodes.

### Strength-based Configuration Generation Module

Since our arm IK system is rooted at the sternum, there are a total of three segments (sternum-shoulder segment, shoulder-elbow segment, and elbow-wrist segment) and five rotation angles (one body rotation angle, three shoulder rotation angle and one elbow rotation angle) that we need to manage.



search, which essentially minimizes the distance to the target guiding node. Given a potential end-effector pose, the IK solver (our strength-based configuration generation module) finds all valid poses under strength and smoothness constraints and sorts them in strength decreasing order. If the pose with maximum strength has no collision with the environment, it is displayed and reach planning continues. Otherwise, it is discarded and the next maximum strength pose from the IK solver is tested for collision. If all poses have been tested, the path planner backtracks to another potential end-effector position. The path planning terminates in success if the target position is visited, or in failure if backtrack happens at the starting position.

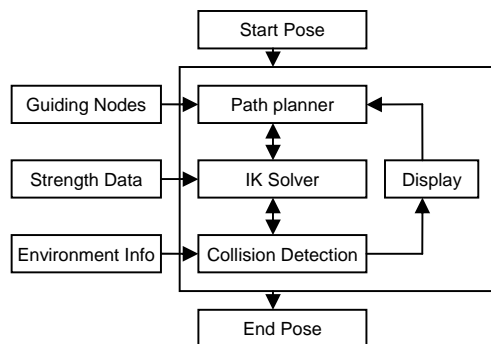


Figure 4. Overview of the system

	Total Search Time(s)	Nodes Searched	Nodes in Solution	Total Length of Solution Path
Collision-free Reach	2.906	83	54	1.07
Rotation Reach	3.172	157	149	2.99
Guided Reach	3.610	170	135	2.69
Chase Reach	10.156	426	282	5.68

Table 2: Statistics of the reach tasks. Total length of solution path is measured in terms of total arm length.

## CONCLUSION

The system is implemented on a P4 1.5GHz desktop PC using C++ and OpenGL. The preprocessing phase takes approximately 6 seconds to partition the workspace into a 3D mesh with 11 cells along each dimension. Four types of reach planning were performed to demonstrate motions that require body rotation and collision avoidance. Statistics about each experiment are shown in Table 2. Animations for the four reach tasks are demonstrated in the Appendix and videos can be downloaded from <http://hms.upenn.edu/SAE05/>. In all the animations, the wrist is set as the end-effector and the final trajectory is shown in red in the last frame.

The system developed in this paper animates a virtual human character to perform collision-free natural reach to different target positions in the workspace at real-time. Such naturalness is guaranteed by evaluating the multi-joint functions against the empirical strength data. The

system does not guarantee completeness in reach planning due to its strength model constraints and its simple path planning algorithm. However, if there is a natural “non-tricky” path that connects the start and target position, the system will find it and it will find it quickly. Also, it is not necessary to assume that the target is in fact reachable.

We plan to acquire data to extract multi-joint function involving waist in order to produce waist-rooted side reach animations. In addition, we plan to incorporate velocity profile to better model the end-effector search process.

## ACKNOWLEDGMENTS

This research is partially supported by NASA NRA NAG9-1279, the National Science Foundation IIS-0200983, the Office of Naval Research (VIRTE) N000140410259, and Lockheed-Martin Corporation.

## REFERENCES

- Case, K., J. M. Porter, et al. (1990). *SAMMIE: a man and workplace modelling system*. Karwowski, W., Genaidy, A.M., and Asfour, S.S., Computer-aided ergonomics: 31-35.
- Chaffin, D. B. and G. B. J. Anderson (1984). *Occupational Biomechanics*. John Wiley & Sons (New York).
- Delleman, N. J. (2003). *Postural behaviour in static reaching sideways*. Digital Human Modeling for design and engineering, SAE International.
- Faraway, J. J. (2000). *Modeling Reach Motions Using Functional Regression Analysis*. SAE Digital Human Modeling for Design and Engineering Conference and Exposition.
- Gil Coury, H. J. C., S. Kumar, et al. (1998). *Measurements of Shoulder Adduction Strength in Different Postures*. International Journal of Industrial Ergonomics 22: 195-206.
- Imrham, S. N. (1983). *Modeling Isokinetic Strength of the Upper Extremity*. Texas Tech University. TX. Ph.D.
- Kavraki, L., P. Svestka, et al. (1996). *Probabilistic roadmaps for path planning in high-dimensional configuration space*. IEEE Trans. on Robotics and Automation.
- Korein, J. U. (1985). *A geometric investigation of reach*. Cambridge MA, MIT Press.
- Latombe, J. C. (1991). *Robot Motion Planning*. Boston, MA, Kluwer Academic Publishers.
- Liu, Y. and N. I. Badler (2003). *Real-Time Reach Planning for Animated Characters Using Hardware Acceleration*. International conference on Computer Animation and Social Agents, New Brunswick, NJ, IEEE Computer Society.

11. Mital, A. and H. F. Faard (1990). *Effects of Sitting and Standing, Reach Distance, and Arm Orientation on Isokinetic Pull Strengths in the Horizontal Plane*. International Journal of Industrial Ergonomics 6: 241-248.
12. Mital, A. and S. Kumar (1998a). *Human Muscle Strength Definitions, Measurement, and Usage: Part I - Guidelines for the Practitioner*. International Journal of Industrial Ergonomics 22: 101-121.
13. Mital, A. and S. Kumar (1998b). *Human Muscle Strength Definitions, Measurement, and Usage: Part II - The Scientific Basis (Knowledge Base) for the Guide*. International Journal of Industrial Ergonomics 22: 123-144.
14. Pandya, A. and A. J. Micocci (1989). *Dynamic Strength Data on the Shoulder, Elbow and Wrist*. NASA Johnson Space Center.
15. Park, W., D. B. Chaffin, et al. (2002). *Modifying motions for avoiding obstacles*. SAE Transactions.
16. Wiley, D. and J. Hahn (1997). *Interpolation Synthesis of Articulated Figure Motion*. IEEE Computer Graphics and Applications.
17. Yamane, K., J. J. Kuffner, et al. (2004). *Synthesizing Animations of Human Manipulation Tasks*. SIGGRAPH 2004.

## CONTACT

Liming Zhao.  
 Center for Human Modeling and Simulation  
 University of Pennsylvania  
 Email: liming@seas.upenn.edu

## APPENDIX



Reach planning animations of four types of tasks with wrist as the end-effector and the trajectory shown in red in the final frame. (a) A simple example of collision avoidance and the green sphere indicates the target. (b) Reach multiple targets (green sphere in each frame) with body rotation involved. (c) Reach planning with guided nodes. Oranges wire cubes in the first frame are generated during initialization phase and represent the valid guiding nodes in the discretized space. The orange spheres in frame 3-5 represent the target while the green spheres are the guiding nodes on the shortest path that lead the end-effector from green sphere in frame 2 to the green sphere in frame 6. (d) Reach planning in which the end-effector chase the arbitrarily moving target, represented as the green sphere.