Experiments in Ergonomic Robot-Guided Manipulation

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Abstract

Repetitive manual materials handling of heavy loads is common in assembly and is a common cause of low back disorders. The manual manipulation of a heavy load may be made more comfortable by constraining the load to move along a guide. The frictionless guide directs the motion of the load to the goal configuration as the human operator provides forces in directions that are comfortable. In this paper we present our first experimental results in guided manipulation with the purpose of understanding motions and forces that are comfortable for human operators.

1 Introduction

We are studying the use of passive guides to assist a human in manipulating a heavy load. A guide acts as a frictionless rail which confines the load to a one-dimensional curve in its configuration space. This is a type of collaborative manipulation: the human and the guide cooperate to move the load from one configuration to another. The guide may be implemented by a fixed rail, but preferably by a programmable constraint machine, such as a cobot. Different examples of cobots are presented in Peshkin *et al.* [24].

Unlike approaches to robot-assisted manipulation based on human force amplification, a guide is a passive device; it redirects the momentum of the load without affecting the energy. A drawback is that this limits the set of tasks to which the approach is applicable. Advantages are that the passivity of the guide makes it inherently safe for human collaboration, and stability problems with high-bandwidth force feedback are avoided. By designing the guide properly, we allow the operator to provide forces in directions that are comfortable while the guide directs the motion to the goal configuration. This approach combines the strengths of the operator (the ability to monitor the progress of the task and to stop the motion in an emergency) with the precise positioning and ergonomic benefits provided by the guide.

Lynch and Liu [19] studied the problem of designing guides which are comfortable for the operator. The idea is based on the observation that of the infinite set of possible guides between the initial and goal configuration of the load, it is easier for the human to manipulate the load along some guides than others. Lynch and Liu formulated the general problem, then focused on the particular case of pushing and pulling a heavy cart constrained to move on a guide. They observed that it is easier to generate large pushing and pulling forces than sideways dragging forces. Based on this, they proposed a simple "ergonomic" objective function for choosing between guides: the cost for an applied wrench by the human is a quadratic function of the wrench, with weighting factors indicating the relative ease with which forces and torques can be generated in each direction. Based on this simple objective function, they derived optimal guides for manipulating a planar cart.

This simple objective function provides testable predictions on how humans will interact with constraints. In our current work, we are interested in the following three problems:

1. Performing human experiments to test the predictions made by the simple quadratic objective function. If actual forces and motions match the predicted, then we have evidence in favor of the model.

2. Refining the objective function based on the experimental data and the biomechanics literature.

3. Finding optimal guides based on the new refined model and testing them with human subjects.

The result of the first two items will be the development of a theory of how humans prefer to interact with frictionless constraints. The result of the third item

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Motion Guides for Assisted Manipulation
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will be the development of practical assistive motion guides.

In this paper we report our preliminary results on experimentally testing the predictions made by the quadratic objective function. Future work will address the remaining two items.

Section 2 reviews previous work on robot-assisted manipulation and objective functions in human motion control. In Section 3 we review the ergonomic model which is put to test in this paper. Section 4 describes the experimental hardware and protocol, and Section 5 gives the results. We conclude in Section 6.

2 Previous Work

Manual materials handling exposes the worker to known risk factors for low back disorder, such as lifting, bending, twisting, pulling, pushing and maintenance of static postures. Nearly half of all manual materials handling consists of pushing and pulling activities (Kumar et al. [18]) similar to pushing and pulling a cart, as studied in this paper.

A great deal of research has been done on physiological and psychophysical aspects of materials handling. Snook and Ciriello [25] have published a large database for designing lifting, lowering, pushing, pulling, and carrying tasks. Other recent work includes studies of spine loading during lifting tasks (Marras *et al.* [21]). Al-Eisawi *et al.* [1] study the effect on the initial forces applied by the human to a push-cart when changing the height of the handle. Kumar *et al.* [18] study the maximum push and pull forces humans can apply for different heights of the handle, and Ciriello *et al.* [5] study the maximum comfortable forces for pushing and pulling a cart.

To increase the safety and productivity of human workers, robot-assisted manipulation has been studied in the robotics community. Kazerooni [13, 14] has pioneered the development of human manipulator extenders, which amplify the human's force capabilities. The stability of a human-robot system is studied by Kosuge *et al.* [16]. Hayashibara *et al.* [10] built a 2DOF power assist robot arm to amplify the torques at the human shoulder and elbow in a vertical plane. Force compensation for gravitational and dynamic loads can be adjusted separately. Homma and Arai [12] and Nagai *et al.* [22] have developed robotic orthoses to assist arm motion for disabled people. A key concern in all of this work is safety, since the human is physically attached to a powerful robot.

In *human-robot coordinated manipulation*, the human is not directly attached to the robot; instead, the human and robot are attached to the load and interact through it (Yamamoto *et al.* [28]; Al-Jarrah and Zheng [2]; Kim and Zheng [15]). Manipulation forces are distributed between the human and the robot. The robot must have some form of compliance control, and it should be able to interpret the human's intentions in terms of the forces sensed at the robot's end-effector. Recently Arai *et al.* [4] have used a robot implementing a nonholonomic constraint for effective human-robot manipulation.

To design an optimal motion guide, we can look to the literature on optimality criteria for human motion. In addition to satisfying the primarily task-oriented objectives, many skilled movements appear to satisfy a more general, common objective, which might be described by such terms as "ease," "economy of effort," or "efficiency" (Nelson [23]). For human arm (shoulder and elbow) point-to-point motions, two popular models are the minimum jerk hypothesis (Flash and Hogan [6]) and the minimum rate of change of torque hypothesis (Uno *et al.* [26]). Alexander [3] calculated arm trajectories to minimize metabolic cost of the motion, based on a model of muscle metabolic rates (Ma and Zahalak [20]), and showed that the resulting trajectories closely match experimental trajectories found by Hollerbach and Atkeson [11]. Gomi and Kawato [7, 8, 9] have studied stiffness profiles of the human arm during point-to-point motion with and without guiding constraints.

For large-scale manipulation of large loads, locomotion is involved. Kram [17] presents evidence that for each type of gait (walking/jogging, walking/trotting/galloping), animals tend to choose the speed that minimizes metabolic cost.

3 An Ergonomic Model

Here we study the case of collaborative manipulation in the horizontal plane. The load is rigidly attached to a tricycle cobot cart (Figure 1). The human pushes on a handle fixed to the cobot, and the cobot cart controls the steering angles of the wheels to allow motion only along a pre-defined curve.

Three frames are defined: an inertial frame $\mathcal{F}^w$, a body frame $\mathcal{F}^b$ fixed to the center of mass of the load, and a human frame $\mathcal{F}^h$ fixed to the body and defining the coordinate system in which forces applied by the human are measured. It is assumed that the human does not move relative to the body being manipulated.

The configuration of $\mathcal{F}^b$ in $\mathcal{F}^w$ is written $\mathbf{r} = (x, y, \theta)^T$. The velocity is written $\mathbf{v} = (\dot{x}, \dot{y}, \dot{\theta})^T$ and the total wrench acting on the cart is $\mathbf{w} = \mathbf{w}_h + \mathbf{w}_g = (\mathbf{f}, \tau)^T =$

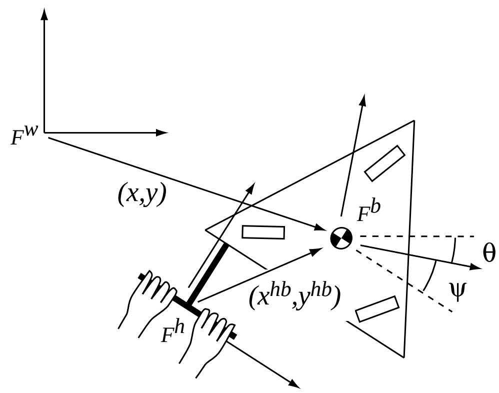

Figure 1: Model of a tricycle cobot.

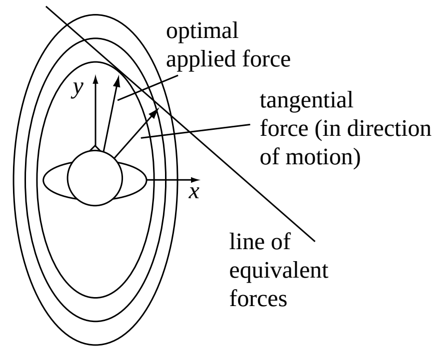

Figure 2: Iso-cost force ellipses for $w_1/w_2 = 4$.

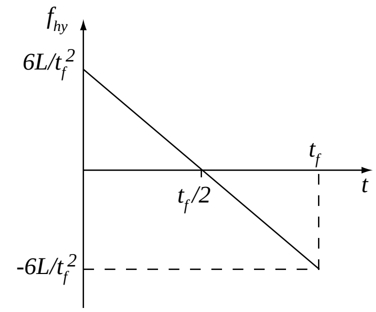

Figure 3: The optimal human force profile $f_{hy}(t)$ for manipulating a unit mass from $(0,0)^T$ to $(0,L)^T$ in time t_f.

$(f_x, f_y, \tau_z)^T$, where $\mathbf{w}_h$ is the wrench applied by the human and $\mathbf{w}_g$ is the (workless) wrench applied by the guide. The configuration of $\mathcal{F}^b$ in $\mathcal{F}^h$ is given by $\mathbf{r}^{hb} = (x^{hb}, y^{hb}, \psi)^T$, (Figure 1). We consider motions beginning and ending at rest, and following Lynch and Liu [19] we consider the quadratic objective function

$$c = \int_0^{t_f} \mathbf{w}_h^h(t)^T W \mathbf{w}_h^h(t) dt,$$

where $\mathbf{w}_h^h$ is the human wrench measured in $\mathcal{F}^h$. The matrix $W = \text{diag}(w_1, w_2, w_3)$ weights the relative cost of the different components of the wrench $\mathbf{w}_h^h$ applied by the human. For instance, awkward twisting and sideways dragging forces could be weighted more heavily than pushing and pulling forces.

An important property of the objective function c is that the shape of the optimal guide is independent of the time of motion. The same guide is therefore optimal regardless of how quickly the human performs the motion.

As a special case of collaborative manipulation in the plane we consider the cobot/load with no rotation. In this 2-DOF case $\mathbf{r} = (x, y)^T$ and $\mathcal{F}^b$ and $\mathcal{F}^h$ are identical and aligned with $\mathcal{F}^w$. We are interested in the optimal guides from the point $A = (0,0)^T$ to the point $B = (x_f, y_f)^T$. The force applied by the human operator is $\mathbf{w}_h^h = \mathbf{w}_h = (f_{hx}, f_{hy})^T$ and the objective function is now

$$c = \int_0^{t_f} (w_1 f_{hx}^2(t) + w_2 f_{hy}^2(t)) dt. \quad (1)$$

In the following, we assume that the weight ratio $w_1/w_2 \geq 1$. Intuitively, motion in the y direction corresponds to pushing and pulling in the human frame, and motion in the x direction corresponds to sideways dragging.

The objective function defines iso-cost force ellipses in the human frame, as shown in Figure 2. Suppose the human wishes to apply a particular tangential force, as shown in the figure. Since normal forces are canceled by the guide, the human is free to choose any normal force to minimize the cost in (1). This gives a line of human forces in the (f_{hx}, f_{hy}) space which yield the same tangential force. The optimal human force is where this line of equivalent forces is tangent to an iso-cost ellipse.

Now, if the goal configuration is of the form $B = (0, L)^T$ and $w_1/w_2 \geq 1$, it is clear that the optimal path is the straight line connecting $(0,0)^T$ and $(0,L)^T$. In this case, a guide provides no ergonomic benefit, and we are simply interested in the shape of the force profile applied by the human. Lynch and Liu [19] show that, in the case where the total mass of the cart and the load is $M = 1$, the optimal force profile $(0, f_{hy}(t))^T$ is a ramp

$$f_{hy}(t) = \frac{6L}{t_f^2}(1 - \frac{2t}{t_f}),$$

as shown in Figure 3. We will return to this result in Section 5.

Optimal guides for different combinations of end positions and weight ratios w_1/w_2 are presented in

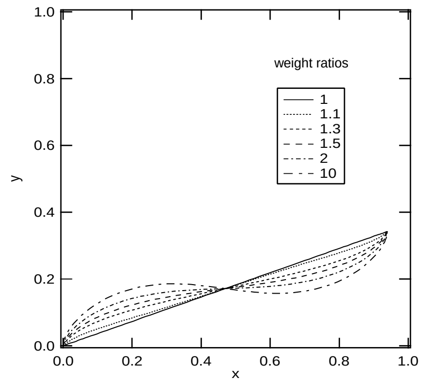

Figure 4: Optimal guides for different weight ratios w_1/w_2 and $\alpha = 20°$.

Lynch and Liu [19]. Figure 4 shows the optimal guides as a function of w_1/w_2 to end positions at an angle $\alpha = 20°$ relative to the x-axis. When $w_1/w_2 = 1$, the optimal guide is a straight line, and the optimal human force profile for interacting with the guide has the same ramp shape as in Figure 3, where the forces applied by the human are tangential to the path. As w_1/w_2 increases, it is more efficient for the human to decrease forces in the x direction, increase forces in the y direction, and let the guide steer the load along a curved path.

4 Experiments

To test and refine the objective function, we have conducted experiments with human subjects interacting with linear guides at angles $\alpha \in \{90°, 75°, 60°, 45°\}$ in the human frame, where 90° is the forward direction.

4.1 The Hardware

We have performed experiments in guided linear pushing using the Scooter tricycle cobot (Wannasuphoprasit *et al.* [27]), and using a trolley moving on a fixed overhead rail system (Figure 5). The fixed rail system is convenient for providing a very rigid constraint for testing purposes. The results we report in this paper are for the rail system.

The trolley handle is a circular cross-section aluminum bar with a diameter of 1in (2.54cm), and the center of the handle is 40in (101.6cm) above the floor. The operator's hands on the handle are separated by approximately 3in (7.6cm). Forces at the handle are collected by a PC at 1000Hz. The force sensor is an ATI Industrial Automation Gamma 15/50 force sensor. The sensor can measure forces in the y direction (forward in the human frame) in a range from -50lb to 50lb (-223N to 223N), and in the x (right) and z (up) directions in the range -15lb to 15lb (-67N to 67N). The mass of the moving trolley is approximately 65kg. At slow walking speeds, the friction force on the trolley is approximately 1.5lbs.

Figure 5: A trolley on an overhead rail system provides a smooth rigid constraint.

4.2 Experimental Protocol

We conducted experiments with linear guides at angles $\alpha \in \{90°, 75°, 60°, 45°\}$ relative to the human frame, fixed to the handle. To change the direction of the linear guide, we simply rotated the handle relative to the trolley and asked subjects to keep their shoulders square to the handle (to satisfy the assumption that the human frame is fixed in the handle frame). The total distance of each motion was 72in (183cm). For each angle, subjects were told to push the load forward in approximately two seconds, rest for two seconds, and then pull the load back to the original position in approximately two seconds.

Before collecting the data, subjects were told to practice the motion four or five times to get used to the feel of the guide. Then data from two motions were captured. Subjects were told to perform the pushing in a natural manner, with the constraint that the shoulders be kept square to the handle. Trials were also performed where subjects kept their elbows locked straight. This further assured that the shoulders would be square.

5 Results

We report the results for a female volunteer, aged 20. The physiological data are:

Mass	150lbs (68kg)
Height	67in (170cm)
Shoulder height	53in (134.6cm)
Elbow height	45in (114cm)
Knuckle height	33in (84cm)

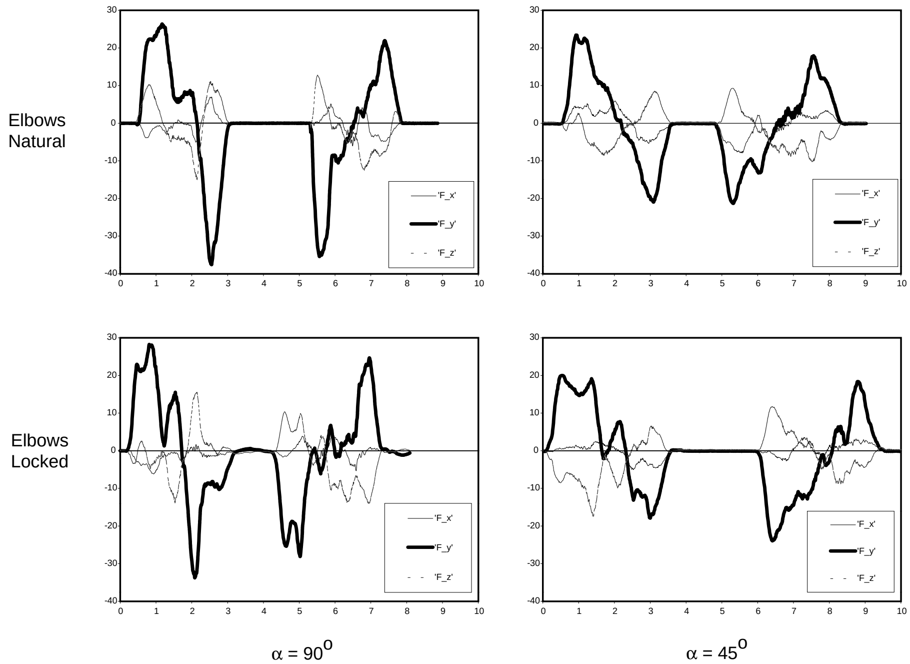

Figure 6: Force (lbs) vs. time (s) from four representative pushing and pulling trials for a single subject. The results in the top row are for elbows in a natural position during pushing, and the results in the bottom row are for elbows locked straight. Results in the left column are for straight-ahead pushes ($\alpha = 90°$) and results in the right column are for a guide at $\alpha = 45°$ in the human frame.

Force data collected from four different trials are shown in Figure 6. These results are representative of other experiments.

Forces in the y direction take an approximately ramp-like profile, as predicted by the objective function (1) when interacting with a linear constraint. Although the forces quickly increase from zero to near their maximum value, this takes nonzero time. In our simple quadratic objective function of the applied force, there is no cost for a discontinuous change in force, and as a result the predicted forces have discontinuities at the beginning and end of the motion. A rate of change of force term could be added to the objective function.

The motion is short enough that the subject does not achieve full-speed walking. With longer motions, we expect the subject will maintain a constant speed during the middle of the motion, providing just enough force to overcome friction at this speed. We could augment our simple model to include a walking velocity term. Note also that the integral of the pushing and pulling forces during a single motion are not equal. This is due to friction.

Maximum pulling forces tend to be larger than maximum pushing forces. Forces in the z direction (up/down, not accounted for in the planar analysis) appear to be coupled to pushing and pulling forces, perhaps because the forces tend to act along the line defined by the hands and the shoulders. The force profiles with locked elbows are less smooth than those where the elbows are allowed to bend naturally. We suppose this is because bending the elbows absorbs variations in the force. When the elbows are locked, force variations are directly transmitted from the cyclical stepping motions.

We did not observe a significant increase in forces applied in the x direction as we decreased the angle α. According to our simple model, this implies a large weight ratio w_1/w_2. In other words, the subjects made use of the constraint by applying forces normal to the constraint. This preliminary data supports the idea that a constraint can make a materials-handling task more comfortable for a human.

Finally, we should note that the objective function (1) is essentially a static model. It assumes that the subject's shoulders are fixed relative to the handle, and the subject walks at an angle determined by α. This may be a bit awkward, and in practice the subject may align the shoulders perpendicular to the direction of motion. This simple model is just our first step at understanding the complex coordinated problem of pushing and locomoting.

6 Conclusion

The results presented here are preliminary, but they support the idea that humans can take advantage of constraints to make a materials-handling task more comfortable. More extensive experiments will be necessary to identify better objective functions expressing the ergonomic cost of pushing and pulling tasks.

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