Motion Guidance Experiments with Scooter Cobot

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Abstract

Cobots assist humans by mechanically guiding motion along software-defined paths or surfaces. Cobot design has been extensively studied previously. This paper reports the first systematic experimental study of motion guidance with a cobot. We investigated the movements of seven operators with the Scooter cobot in representative environments. Analysis of the force exerted by the operators and the trajectories reveals significant differences between guided movements (GM) and free movements (FM). While FM requires learning for each novel task, GM is optimal from the first trial: Less effort is required to move in GM than in FM; Movements in GM are faster, smoother, and require less back and forth correction than in FM. These advantages demonstrate the strength of the Cobot concept. The results further suggest that operators guided by the Scooter can handle objects in a more "open-loop" way than with a dumb trolley, and so perform faster and concentrate on other aspects of the manipulation task, potentially resulting in increased productivity and fewer injuries.

1. Introduction

Placing a window or a car door into its frame is a difficult operation requiring simultaneous control of six degrees of freedom (DOF). Mechanical guides, such that only translation is needed, would make it easy to move it into the frame using only translation. Cobots (or **Co**llaborative ro**bots**) developed by M Peshkin and JE Colgate at Northwestern University [1–4] are robotic assisting devices implementing a similar strategy. Unlike fixed mechanical guides, cobots realize software-defined mechanical guideways along desired paths or surfaces. They are passive in that they do not generate motion, but only steer the wheels to direct it to realise software-defined paths[4]. Forces perpendicular to the wheel headings are balanced by friction, constraining motion to the heading direction.

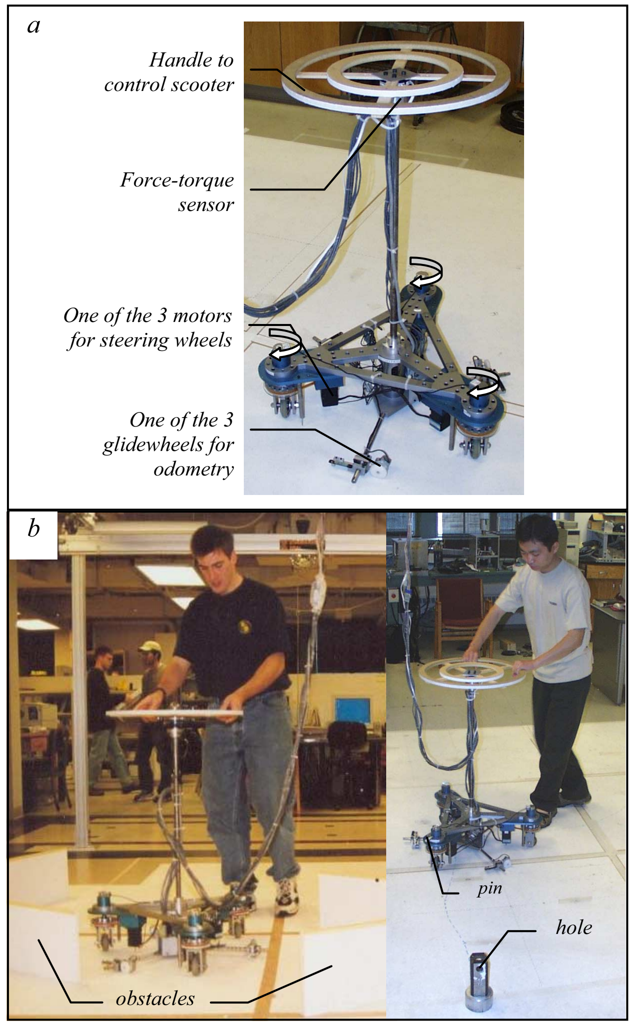

Figure 1. *a*: Scooter cobot to guide planar motion in position and orientation. *b*: Two subjects performing path design tests at LIMS, Northwestern University.

To illustrate the cobot concept and its motion modes, we briefly describe the *Scooter cobot* with which the experiments reported in this paper were performed. The Scooter (Fig 1a) is a triangular vehicle moving on a plane, with a steerable wheel at each corner. In *Free Mode* (FM), the wheels turn like casters to align with the force

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exerted by the operator, and the cobot behaves as if it had 3 DOF (i.e., planar position and orientation). This force is measured by a force-torque sensor mounted on the handle. In *Guided Mode* (GM), each wheel is steered by a motor to follow a guiding path coded in software.

Cobot kinematics, design and control have been investigated extensively, and several planar and spatial cobots have been realized for the automotive industry [1–4]. The strategy of mechanically guiding motion is not limited to the automotive industry. It could be used, for example in surgery, to facilitate manipulation and keep a scalpel out of risk areas; to facilitate physical rehabilitation (see the Unicycle Two-Link Arm project in [3]); or to create an adaptable wheelchair that assists the handicapped according to their abilities [5].

While it is expected that motion guidance can facilitate object handling, we know of no systematic study on motion guidance with a cobot. A few previous studies on the interaction with kinematic constraints have been realized on the multi-joint arm. [6] studied forces at static positions in the presence of kinematical constraints, and [7] studied stiffness adaptation in constrained movements. However, these works do not address questions such as *whether and how motion guidance facilitates objects handling,* and *how do operators use motion guidance*. The present work investigates, for the first time, real motions performed with a cobot. We recorded the force exerted during movement by the operator and the trajectories realized in various environments and conditions with the Scooter cobot. We further compared the behavior in guided and in free modes. Our results show how operators use the cobot to facilitate object handling. In particular, little force and visual feedback were required in guided mode. The operators relied on the guideway to maneuver the Scooter without exerting much force against it. Tools to program cobots based on this paper are presented in [8].

2. Methods

a. Subjects

The experiments were approved by the Institutional Review Board of Northwestern University, and performed by seven students (mean age 24, with standard deviation 2) without known motor disability. These subjects were informed about the experiments, and gave their consent prior to participation.

b. Training

Consecutive movements performed with the Scooter in a given environment may vary significantly (Fig.4). Therefore, the subjects were first trained to drive the Scooter in guided and free modes in three typical environments: along a straight line (Fig. 2a), along a curved line (Fig. 2b), both drawn on the floor, and through a narrow passage (Fig. 2c). The subjects were required to follow the line and place a pin fixed to the Scooter into a hole at its end of the path. Corresponding guiding paths were provided to train the subjects on guided motion. The subjects also had to maneuver the Scooter through a passage (Fig. 2c) narrower than the maximum diameter of the Scooter and to place the pin into the hole. The obstacles were made of Styrofoam boards (Fig. 1b). Again, a corresponding guiding path was used to train on guided motion.

For all three paths the subjects were trained first in guided mode and then in free mode, in the order of Fig. 2. They were required to perform at least three trials in each. For the drawn lines, learning was considered complete when the mean distance between the desired and realized path was less than 0.2*m*. For the narrow passage, learning was complete when no obstacle was hit. On average, subjects required 5 trials (minimum 3, maximum 6) in each environment. The training session took an average of 71 minutes with a standard deviation of 3.3 minutes for each subject.

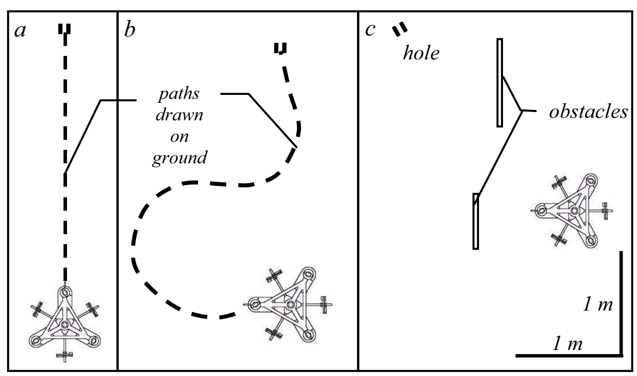

Figure 2. Three environments the subjects used to learn to move with the Scooter cobot.

c. Performance in Free and Guided Modes

Performance after learning was tested the next day in the two environments of Figure 3. To test free motion, subjects had to move six times from the start point to the end point without colliding with any obstacle, and to place the pin into a hole at the end point. These six paths were then least-square approximated using B-splines with

16 control points [8], used as guiding paths. So each free movement had one corresponding guiding path and one guided motion.

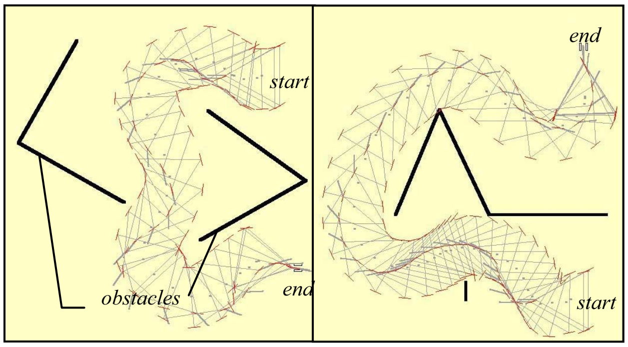

Figure 3. The two environments in which free and guided motion were tested. Free movements are shown in this figure.

d. Data Analysis

We want to compare the *effort* to perform movement in free and guided modes. Obviously the energy $E = \int \mathbf{F} d\mathbf{l}$ cannot be used for this purpose, as it does not consider internal forces. For example if a subject guided along a path stops at a position and exerts a force normal to the guideway, the corresponding energy (used by the muscles, though not transformed into work done on the object) is not accounted for in E. We measured the effort

$$\varepsilon(\boldsymbol{\tau}) = \mathrm{T}\int_0^{\mathrm{T}} |\boldsymbol{\tau}| dt \qquad (1)$$

to rotate the Scooter, and the "transverse effort"

$$\varepsilon(\mathbf{F}_\perp) = \mathrm{T}\int_0^{\mathrm{T}} |\mathbf{F}_\perp| dt\ . \qquad (2)$$

to redirect movement. Similarly, [9] used the integral of a quadratic function of the wrench $\mathcal{F} = (\tau, \mathbf{F})$ to measure the effort during a movement. The movement duration multiplier T (defined as the time with translational velocity exceeding 0.015 *m/s* and rotational velocity exceeding 0.003 *rad/s*) makes these measures invariant under time scaling, *i.e.*, two movements $\mathbf{x}^1(t)$, $t \in [0, \mathrm{T}]$, and $\mathbf{x}^2(t)$, $t \in [0, \mathrm{T}/\alpha]$, with $\mathbf{x}^2(t) \equiv \mathbf{x}^1(\alpha\, t)$, $\alpha > 0$, have the same measure. In guided mode, it would be theoretically possible to complete a movement from the start to the end point with zero torque or perpendicular force, i.e., with $\varepsilon(\tau) = \varepsilon(\mathbf{F}_\perp) = 0$, as the Scooter needs only a motive force tangent to the guideway.

Operators sometimes needed back-and-forth corrections to accurately position the Scooter. We counted corresponding *direction reversals* by the following criterion: there is a reversal when the dot product between the current (translational) velocity vector and any velocity vector less than 2.5 cm away from the current position is negative, and checked visually whether it did correspond to a reversal (fig 7b).

Fast Fourier Transform (FFT) gave the *frequency content* of the force and torque exerted by the operator on the cobot. We used the integral of normalized FFT_N

$$\sigma(\boldsymbol{\tau}) = \int_0^{v_s} FFT_N(\boldsymbol{\tau}) dv \qquad (3)$$

and

$$\sigma(\mathbf{F}) = \int_0^{v_s} FFT_N(\mathbf{F}) dv \qquad (4)$$

to compare the frequency content of torque and force between free and guided motion in the interval $[0, v_s]$ *Hz* where $v_s = 500$ *Hz* is the Nyquist frequency which is half the sampling frequency of 1kHz. As low frequencies correspond to the path shape and so are similar in FM and GM, the FFT in either FM or GM was normalized by the largest amplitude to give FFT_N. Hence the differences $\sigma(\tau_{FM}) - \sigma(\tau_{GM})$ and $\sigma(\mathbf{F}_{FM}) - \sigma(\mathbf{F}_{GM})$ measure the difference in high frequency content between FM and GM.

Directional t-tests were used to investigate learning-related features and compare GM with FM, after Lilliefors tests on the data to confirm that they were T-distributed.

3. Results

a. Learning

Fig. 4 shows initial trials characterized by alternating clockwise and anti-clockwise torques and corresponding oscillations in the trajectory. Further, the torque gradually decreased with repetition of the movement, but remained larger than in guided mode. We examined this trend systematically using the effort measure $\varepsilon(\tau)$ (defined in the Methods as the integral of the torque). Figure 5 shows the evolution of the normalized effort measure $\underline{\varepsilon}(\tau) = \varepsilon(\tau)/\varepsilon_{max}(\tau)$ as a movement was repeated, where ε_{max} is the maximum $\varepsilon(\tau)$ in that environment for a given subject.

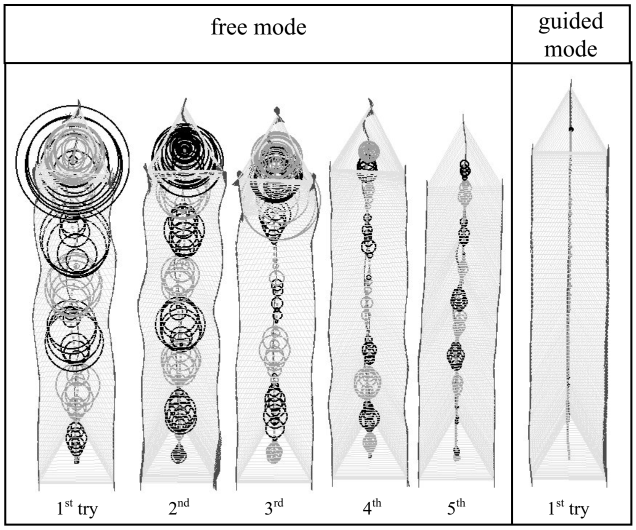

Figure 4. Torque in consecutive free motions repeated along the straight line. Clockwise torque is depicted by grey rings and anti-clockwise torque by black rings. The mean speed was 0.74 m/s in the fifth free motion and 0.88 m/s in the first guided motion.

The (normalized) effort measure $\underline{\varepsilon}(\tau)$ showed significant change in FM but not in GM. The standard deviation of $\underline{\varepsilon}_{FM}$ is significantly larger than 0.1 ($p<0.02$ for each environment of Fig. 2), while that of $\underline{\varepsilon}_{GM}$ is significantly smaller than 0.04 ($p<0.01$). For all subjects and environments, FM also required significantly more effort $\underline{\varepsilon}(\tau)$ than GM, as $\min(\underline{\varepsilon}_{FM}) > \max(\underline{\varepsilon}_{GM})$ ($p<0.04$): see first column of Table 1. Finally, the data show highly significant learning in the straight and curved environments, but not in the narrow passageway (second column of Table 1).

environment	$\min(\varepsilon_{FM})>\max(\varepsilon_{GM})$	$\varepsilon_{FM,\ untrained}>\varepsilon_{FM,\ trained}$
straight path	0.001	0.005
curved path	0.034	0.009
narrow passage	0.016	0.126

Table 1. Significance level for the difference of applied effort between FM and GM (1st column) and for learning in FM (2nd column).

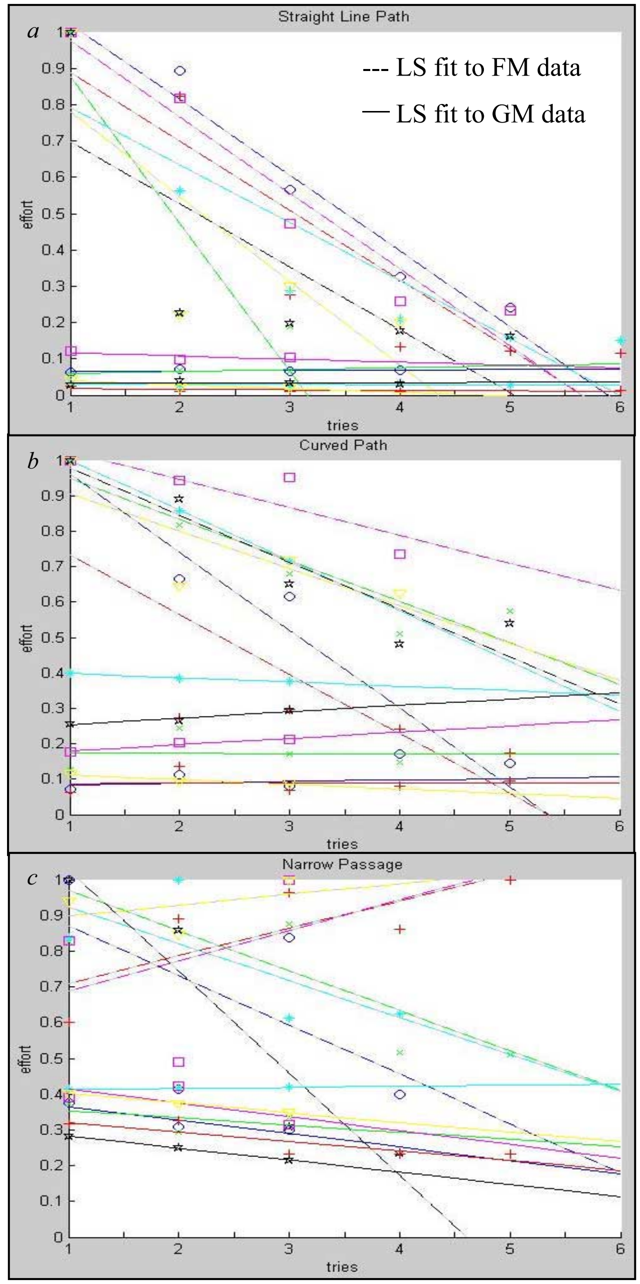

Figure 5. Evolution of rotation effort during learning in the three environments. Each colour represents one of the seven subjects. The dashed lines are LS fits to FM data of the subjects, and the solid lines to GM data.

b. Comparison between Free and Guided Motion

After learning, the subjects applied significantly more torque in FM than in GM (Fig. 6). Fig. 6c further shows a significant difference $\varepsilon(\tau)_{FM} - \varepsilon(\tau)_{GM}$ of rotation effort between FM and GM ($p<0.002$). Finally, the transverse effort $\varepsilon(\mathbf{F}_{\perp})$ is not significantly different in FM and GM ($p>0.2$). Similar results were found using the total force $\varepsilon(\mathbf{F})$, defined similarly to $\varepsilon(\mathbf{F}_{\perp})$, as integral of the force $\mathbf{F}$.

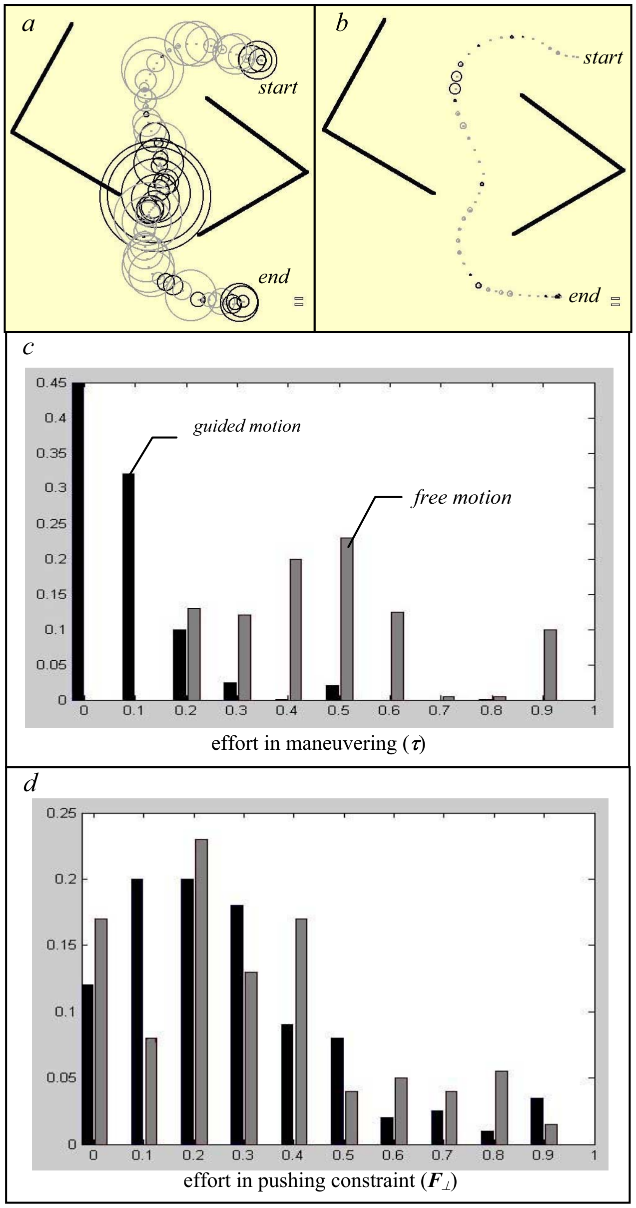

Figure 6. The applied torque was larger in free than in guided motion. In *a* and *b*, the grey and black rings represent anti-clockwise and clockwise torque respectively. The Scooter is not shown to improve visibility. *c*,*d*: Histograms of rotation effort measure $\varepsilon(\tau)$ and transversal effort measure $\varepsilon(\mathbf{F}_{\perp})$, between free (grey) and guided (black) motions done by seven human subjects. *c* shows that the rotation effort $\varepsilon(\tau)$ is higher for FM than for GM, while *d* shows that the difference is not significant for the transversal effort $\varepsilon(\mathbf{F}_{\perp})$.

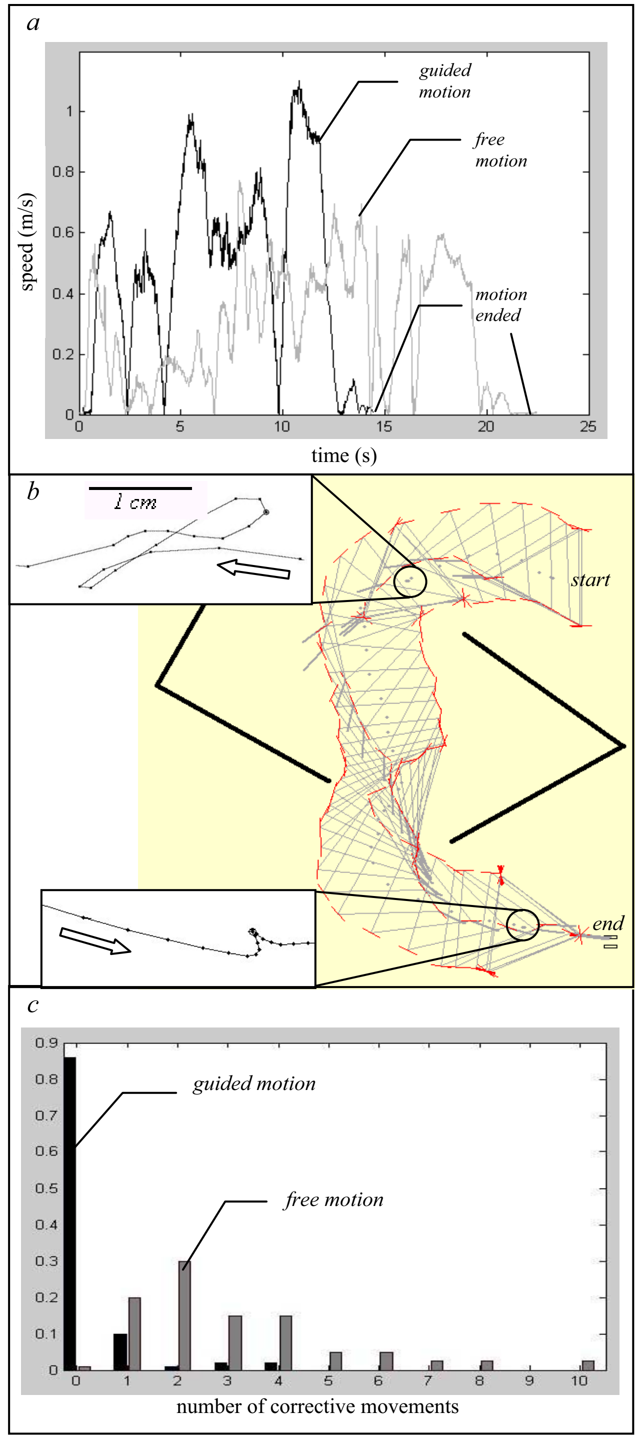

Figure 7. Differences between free and guided motion. *a*: Speed in a guided motion and in the corresponding free motion. *b*: A movement with two direction reversals. *c*: Histogram of the number of direction reversals.

The subjects took less time to complete the same path in GM than in FM ($p<0.005$) (Fig. 7a). As the distance is the integral of the speed, one may expect the mean speed to be significantly larger in GM, so that the area under the speed curves would be similar in FM and GM. However, the mean speed in GM is larger by only 0.04 *m/s* in mean over the subjects. The longer time taken by FM is probably due to more back-and-forth corrective movements in FM than in GM. A t-test confirmed that there are more direction reversals in FM than in GM ($p<0.002$) (Fig 7b, c).

Motions in GM showed smaller high frequency content than in FM (Fig. 8). As the FFT for either FM or GM was similar in all environments, we used its mean over the two environments in Fig. 3. The torque contained significantly more high frequencies in FM than in GM ($\sigma(\mathbf{F}_{FM}) > \sigma(\mathbf{F}_{GM})$ with $p<0.01$). The force generally contained more high frequencies in FM than in GM, but the difference was not significant ($\sigma(\mathbf{F}_{FM}) > \sigma(\mathbf{F}_{GM})$ with $p>0.2$).

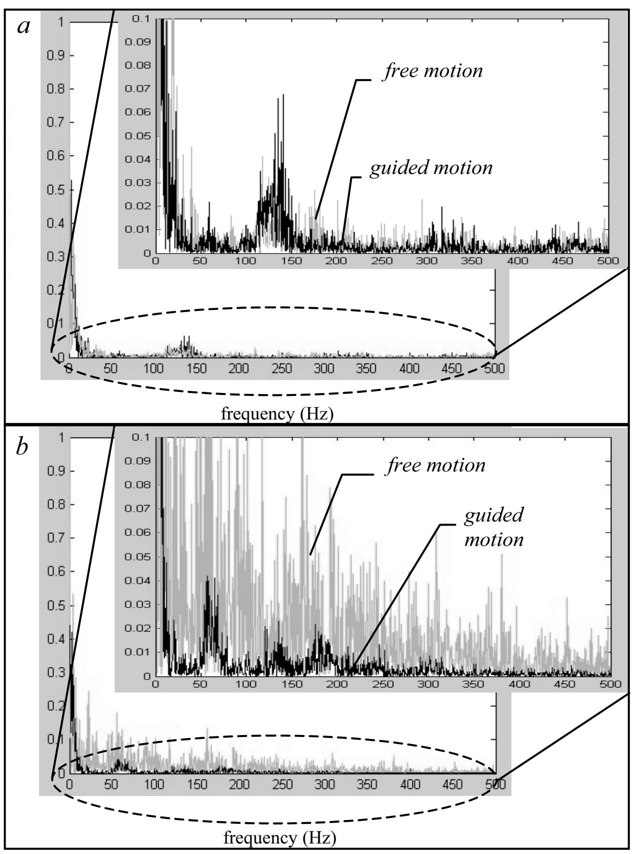

Figure 8. Typical FFT of the applied force (a) and torque (b) in free (grey) and constrained (black) motions. The amplitudes of the high frequency components in free motion are higher than that in guided motion, in particular for the torque.

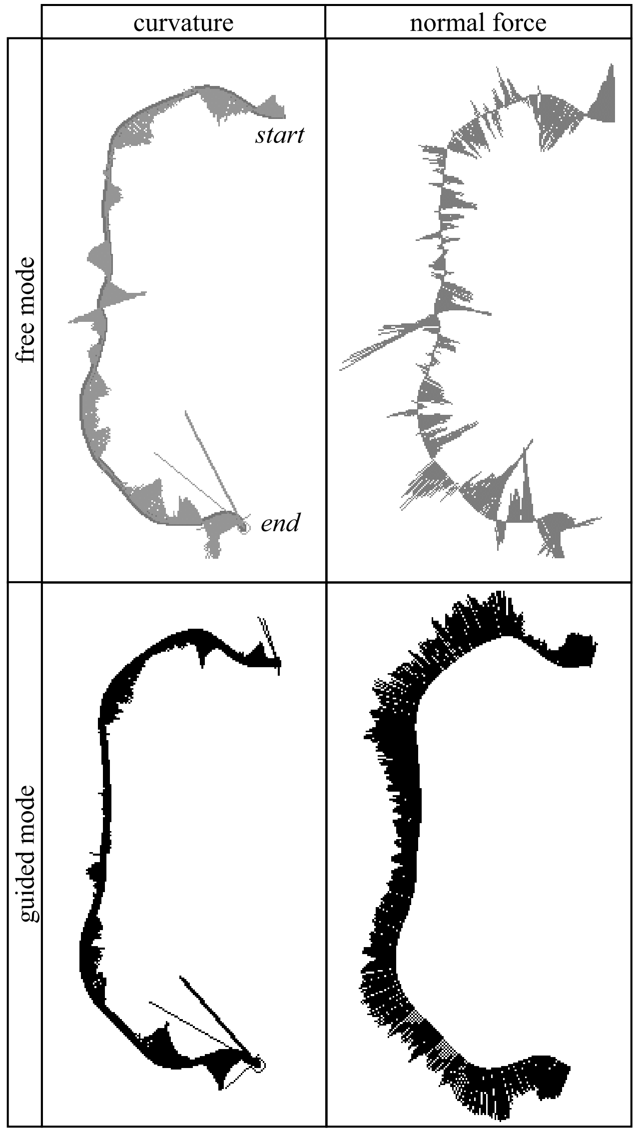

Figure 9. Correlation between normal force and curvature. The figure shows curvature vectors (left) and normal force (right) for a movement in free mode (top, grey) and in guided mode (down, black).

To further compare GM with FM, we computed the correlation between the force normal to the path and also normal to the path — the curvature (Fig. 9). A high correlation coefficient indicates that the operator is providing a centripetal force to move the Scooter along a curve. Therefore a high correlation is expected in FM. However, in GM, the operator does not have to provide centripetal force to turn, and the correlation coefficient becomes an indicator of the motion strategy used by the operator. A large (positive) correlation would indicate that the operator turns with the curve, while an operator just pushing straight will produce force anticorrelated (i.e. negatively correlated) with curvature.

The correlation coefficient between the FM normal force and the curvature was a mean 0.6 with a standard deviation 0.1. In GM, normal force and curvature were uncorrelated, with a mean coefficient of 0.0 and a standard deviation of 0.1.

4. Discussion

From the results of the experiment, movements with the Scooter cobot are fundamentally different in guided mode (GM) versus free mode (FM):

1. For simple environments, performing optimally in FM required several training trials. However, in complex environments, optimal FM movement was hard to achieve and performance did not significantly improve with practice. In contrast, the behavior in GM was optimal from the first trial.
2. Significantly more effort was required to manoeuvre the Scooter in FM than in GM.
3. In GM, the operator can rely on the constraints to guide the movement and excessive normal forces are counteracted by friction. Therefore, we might expect that larger normal forces to be used in GM and in FM. However, even in highly curved paths, the total normal force was similar in GM to that in FM, or smaller.
4. Movements in GM were significantly faster, and had fewer back-and-forth corrective movements than in FM.
5. The high frequency content of applied torque was lower in GM than in FM, indicating smoother motions in GM.

These points demonstrate the advantages of the guided mode, and show the strength of the Cobot concept.

These results were obtained with a particular cobot, the Scooter, and planar motion. Can we expect similar results for general motion guidance involving six degrees of freedom and load support against gravity? The Scooter, reduces a 3DOF motion guidance task to a 1D one. A 6 DOF task reduced to a 1D task may yield similar or even more dramatic differences. Thus similar improvement may be expected in 6DOF manipulation guided by cobots.

The above results also reveal how the operators behave when using the Scooter in guided mode. The fact that motions were smoother in GM and had a smaller number of corrective movements suggests that operators needed less on-line visual control for guided than for free motion. The operator, released from the burden of manoeuvring, can perform faster and concentrate on other aspects of the task [8], e.g., precision and safety, perhaps resulting in improved productivity and ergonomics.

How do operators use motion guidance? If they were turning the cobot by themselves to minimize effort [10], their normal force would be correlated with curvature. However, the correlation coefficient was not positive, showing that the operators used the guideways to manoeuvre the cobot. It would not be surprising that the operators used the constraints to facilitate motion and we may expect that the price to pay for moving easily along a guiding path is higher normal force. If the operator would push the cobot straight, without knowledge of the path, it may be expected that the normal force would be large and anticorrelated with curvature. However the normal force was relatively small and not (anti)correlated with curvature, indicating that the operators did not just push the cobot straight. Perhaps the haptic information received through normal force helped the operator to keep pushing mainly in the correct direction. Guided by the cobot, the operator needed little force and visual feedback to perform complex motion faster.

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