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Usability of Haptic Volumetric Assistance for Surgical Navigation Tasks

Abstract: Manual control of surgical instruments represents a sensorimotor control task with at least 3-6 degrees of freedom (DoF). The impact of haptic guidance on volumetric navigation tasks, such as milling of planned volumes for prosthesis fits or preserving sensitive tissues, is investigated. Interaction centered studies are performed to evaluate the usability of the assistance modes for navigation within a volume, along the surface of a volume and around forbidden regions. Results show that haptic assistance can reduce the number of constraint violations, if the virtual stiffness is high enough. However, haptic assistance also can increase error rates when counterforces are close to the absolute perception threshold, as a false sense of security can arise. For navigation along complex surfaces bilateral haptic constraints should be preferred, while unilateral constraints are sufficient for simple geometries. This study complements previous publications as a basis for a flexible rule-based selection or adaptation of modular haptic assistance systems.

Keywords: Shared Control, Haptic Assistance, Cooperative Surgical Robotics

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1 Introduction

Manual control of surgical instruments represents a sensorimotor control task with at least 3-6 degrees of freedom (DoF). In orthopaedic surgery and neurosurgery, the therapeutic success correlates to the precision with which surgical plans are implemented [1]. Robotic systems can support surgeons to perform complex surgical manipulation tasks with superhuman levels of precision and repeatability while also decreasing workloads [14].

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Teleoperated robotic systems allow versatile assistance, like motion and force transformation, because of the physical decoupling between surgeon and surgical tool. However, direct haptic feedback information is lost. Haptic feedback can be restored by using force-torque sensors at the slave robot, but stable control with haptic feedback in environments with different magnitudes of compliance was proven to be difficult and still subject of current research [3]. In addition to haptic feedback, teleoperated robotic systems enable haptic guidance, where auxiliary forces are generated at the master site to support the execution of surgical plans [14].

Previously, we presented, in accordance to Troccaz' [4] kinematic classification of surgical tasks, how haptic guidance can improve pose finding and three-dimensional path tracing tasks [13], multiparameter control tasks [15] and other surgical use cases, like pedicle screw placements or craniotomies [16]. We evaluated our findings for bone milling tasks in lab studies with a prototype of a cooperative surgical telemanipulator [17]. This works complements previous research by presenting modular volumetric constraints for haptic guidance in telesurgery and evaluates the developed guidance in user studies representing common surgical tasks, like milling prosthesis fits or protecting sensitive tissues.

2 Methods

2.1 Assistance Design

Assistance modes are proposed in accordance with Turro et al. [2], who suggested three general types of constraints for surgical tasks: 1. surface constraint mode (SC), 2. volume constraint mode (VC) and 3. forbidden region virtual fixtures (FRVF). The assistance system is designed in three steps in accordance to Bowyers [5] active constraint implementation framework: Constraint definition, constraint evaluation, and constraint enforcement.

Constraints are defined as surface models with uniformly distributed point clouds and outwards facing normal vectors. Point clouds are the output of 3D scanners, stereo endoscopes or tracking systems and therefore occur frequently in the medical application field. Three different volume geometries with increasing degrees of complexity are chosen: sphere, torus, and block (cuboid with 5 protruding pegs) (Figure 1).

Constraint evaluation is performed by detecting collisions between the virtual tooltip, modelled as a sphere, and the

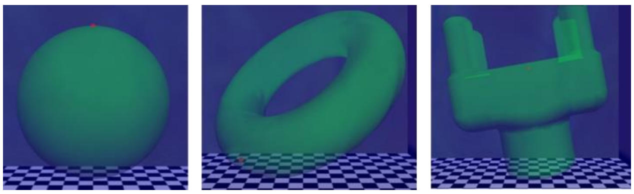

Figure 1: Constraint volume geometries sphere, torus, block (right to left) (adopted from [18])

constraint volumes. The chosen approach is an adaptation of the algorithm of El-Far et al. [6]. For performance reasons the constraint evaluation is performed in an offline pre-processing step and an online collision detection step. During pre-processing every volume geometry is assigned a boundary sphere as a coarse approximation of the constraint volume. Furthermore, the volume's point cloud is partitioned in groups of equidistant overlapping spheres with a maximum of 1000 points per group. Online collision detection is then performed in two steps: In the broad phase collisions between the tool tip and the boundary sphere are detected. In the narrow phase tooltip collisions with the spherical subgroups are identified. For this small subset of points, a proxy method is used to determine penetration depth and direction [5].When the penetration depth is smaller than a defined safety margin the proxy is displaced along the volume surface to the closest surface point, if a maximum displacement rate is below a limit. However, when the penetration depth exceeds the safety margin, the proxy is locked in place, to guide the user out of the constraint, without causing additional damage.

Constraints are enforced with impedance control based on a spring model with experimentally tuned stiffness. In VC/SC an isotropic stiffness is chosen ($p=0.5$N/mm) while in FRVF the stiffness orthogonal to the surface is reduced ($p_o=0.2$ N/mm), to prioritize the reset of tangential deviations and thereby possibly reduce damage caused by pulling out the tooltip.

2.2 Experiment Setup

Experiments are performed with a 6 DoF haptic device Phantom OMNI (Sensable Technologies, Wilmington, MA, USA), which was controlled with Matlab Simulink (The MathWorks Inc., Natick, MA, USA) in combination with the real-time control software QUARC (Quanser, Markham, ON, Canada). As the assistance model is implemented and evaluated within a virtual environment without a slave robot for this study, haptic feedback, tool tracking, anatomy registration and latencies are not considered within the scope of the presented investigations. Instead, the focus is on investigating the usability of the designed assistance system based on the DIN EN 60601-1-6 criteria effectiveness, efficiency, and user satisfaction, while learnability is not considered here in our formative usability studies.

A graphic user interfaces presents the virtual environment in three orthogonal views including the virtual objects and the virtual tool tip position to the study participants (Figure 2,

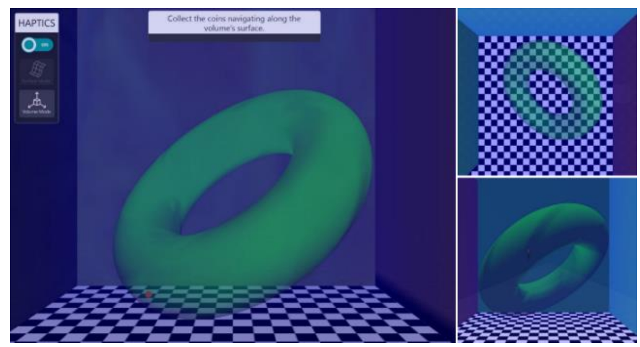

Figure 2: Graphical user interface in experiment 1 (adopted from [18])

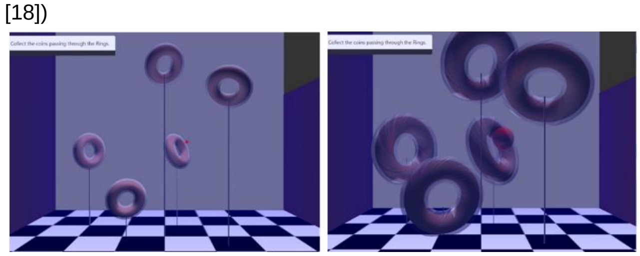

Figure 3: Graphical user interface in experiment 2 (left: small forbidden region; right: large forbidden region) (adopted from [18])

Figure 3). Additionally, in experiment 2 horizontal lines below the volume constraints and a chessboard pattern floor were used to facilitate depth perception in accordance to Wickens et al. [19]. Virtual objects were presented as semi-transparent to always ensure tooltip visibility, while the colour scheme was chosen in accordance to DIN EN ISO 9241-12 (green: no penetration, yellow: penetration withing safety zone, red: critical penetration).

Usability of haptic guidance was evaluated in two experiments: In experiment 1a. users were instructed to navigate the virtual tooltip to five positions within a volume without moving out of the volume. Volumes were presented with an additional safety offset of 5 mm. In experiment 1b. users were instructed to navigate the virtual tooltip to five positions on the volumes surface without deviating from the surface along the way. In experiment 2 users were instructed to subsequently move the tooltip to five positions within the workspace without crossing forbidden regions placed within the virtual workspace.

Independent variables in experiment 1 were the provided haptic guidance mode (1a: VC, no assistance; 1b: VC, SC, no assistance) and the volume constraint geometry (sphere, torus, block). In experiment 2 the size of the forbidden region (small, large) (Figure 3) and the size of the safety margin (0mm, 2mm, 5mm, 10mm) were variated.

Dependent variables were chosen in accordance to usability evaluation parameters as follows:

- Effectiveness
  - Number of boundary penetrations (exp. 1a)
  - Mean deviation from surface (exp 1b)
  - Number of forbidden region penetrations (exp 2)
- Efficiency
  - Time to reach required position
- User Satisfaction
  - Perceived workload according to NASA TLX questionnaire

Thereby, the NASA TLX score provides insight into the subjective workload perception, which is a potential impact factor on user satisfaction.

The experiments were performed by 10 subjects (8 male, 2 female, 1 left-handed) aged between 21-30 without prior experience with the system. No subject had known disabilities impeding their task execution. Users performed both experiments in a randomized order to counterbalance possible learning effects. Before performing the experiments, users received an introductory presentation to explain the tasks they need to perform and then are invited to familiarize themselves with the system with the help of an interactive tutorial. Study participant were told to prioritize precise navigation, while execution time was of subservient importance.

3 Results

In total 10 participants performed 6 test runs in experiment 1a, 9 test runs in experiment 1b. and 8 test runs in experiment 2, navigating to 5 positions during each trial. For statistical analysis, the analysis of variance (ANOVA) and post-hoc tests with Tukey-Kramer are used ($\alpha = 0.05$). For experiment 1a. unpaired t-tests are used instead as only two modes are compared.

Experiment 1a: Navigation within a volume

Without haptic assistance individual participants moved out of the constraint up to 2 times for the sphere constraint, up to 3 times for the torus constraint and 11 times for the block constraint. Out of 10 subjects at least one deviation outside the volume occurred with 5 subjects for the sphere and torus geometry and for 9 subjects in the block geometry. With VC mode assistance no subject moved outside of the safety zone of the constraint geometry.

The average duration to complete a test run, decreased for all geometries, however statistical significance was only found for the torus constraint **(**Figure 4).

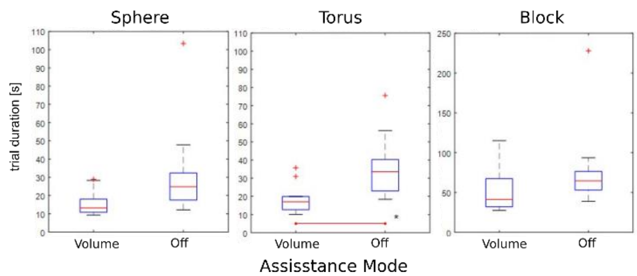

Figure 4: Duration to complete a test run for navigation within a volume (ordinate scaling adapted for 'block')(*: $p<0.05$) [18]

Nasa TLX scores showed not observable differences between VC mode and no assistance for subject's perceived workload.

Experiment 1b: Navigation along a surface

Subjects deviated significantly less from a surface with SC and VC mode compared to no assistance for the sphere constraint, while for the other constraint geometries significance could only be proven for SC mode (Figure 5). The test runs were completed significantly faster with SC and VC mode compared to no assistance. Nasa TLX scored showed significant decrease of perceived mental load with SC mode compared to no assistance (Figure 6).

Experiment 2: Navigation around forbidden regions

Without haptic assistance subjects penetrated up to 7 times with large but only 2 time with small FRVFs (Figure 7). With haptic safety zones subjects penetrated only once, except with large FRVS and 2mm safety zone. The number of subjects which penetrated forbidden regions at least once is highest with 2mm safety zone, followed by no assistance and smallest for assistance with higher safety zone sizes. One exception is a large FRVS with 10 mm safety zone, where a slight increase was measured. Regarding test run duration and perceived mental workload no differences could be seen for different safety zone sizes.

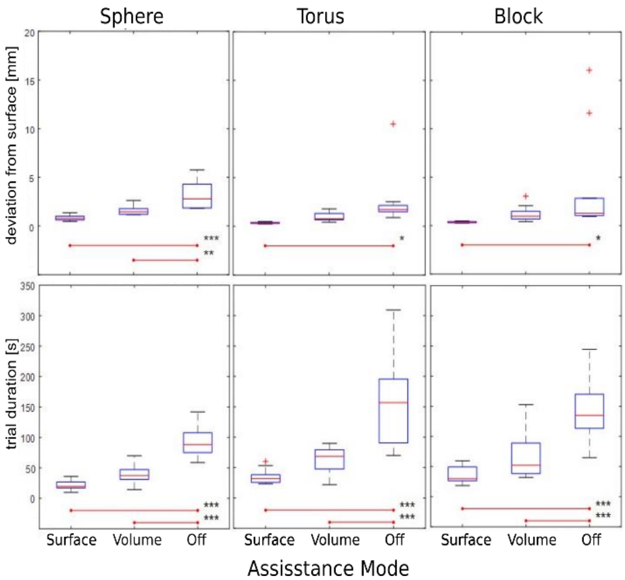

Figure 5: Deviation from surface and trial duration for navigation along a surface (**: $p<0.01$, ***: $p<0.001$) [18]

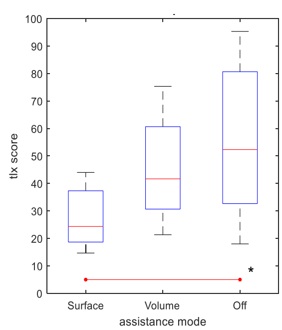

Figure 6: Perceived mental workload for navigation along a surface(*: $p<0.05$) [18]

FRVF size	Small				Large			
Safety zone [mm]	10	5	2	Off	10	5	2	Off
penetrations	0-1	0-1	0-1	0-2	0-1	0-1	0-2	0-7
at least one penetration	20%	20%	40%	30%	50%	40%	70%	50%

Figure 7: Number of penetrations during navigation around forbidden regions (*: $p<0.05$) [18]

prosthesis fits or removal of cancerous bone tissues. In the second experiment the navigation around forbidden regions was tested, an important task for example in ENT surgery to preserve nerves, blood vessels and other sensitive tissues.

4 Discussion

In the medical field haptic volumetric feedback was proposed for surgical simulation [8][10][20], interaction with volumetric image data [9][11], and application with cooperative surgical robotics [12]. Our study reviewed the impact of volumetric haptic assistance for 3D navigation tasks with 2D visual displays. While 3D visual displays can be used to provide life-like spatial cues, haptic assistance provides the benefit of direct bidirectional control, enabling cooperative task execution [7].

For moving inside a volume, results show that haptic assistance (VC) prevented subjects from crossing volume borders. Furthermore, results indicate that subjects navigated to positions faster with VC, although significance could only be proven for the torus geometry. For the complex block geometry, the lack of significance might be because subjects stayed within the volume with VC assistance, while almost all subjects moved out of the volume at least once without assistance and thereby might have used shortcuts.

For moving along a volume surface, the average deviations were significantly smaller with SC compared to no assistance for all geometries, while with VC this was only the case for the sphere. Reason for this may be, that with a unilateral constrain (VC) no feedback is provided for deviations to the inside of the volume and subjects compensate the lack of information by pushing to the outside of the boundary constraint. This strategy restores haptic feedback, however, inevitably leads to deviations with impedance-type haptic assistance. Difficulties to navigate along the surface with VC is reflected by the subject's own perception of the mental workload, which is only with SC significantly smaller compared to no assistance. Despite that, trial durations were significantly shorter with both SC and VC compared to no assistance regardless of the constraint geometry.

For navigation around forbidden regions individual subjects penetrated large forbidden regions more often than small ones, as the prior filled up more of the workspace. Constraint violations could be reduced with safety zones larger than 2 mm but not prevented completely, which might be because the virtual stiffness was too low (0.2 N/mm). Safety zones of 2 mm provide maximal counterforces of 0.4 N, which may be below the absolute perception threshold [21]. A false sense of security might explain why more constraint violations occurred with 2 mm safety zones compared to no assistance.

However, even larger safety zones (10 mm) did not provide sufficient counterforces (2.5 N) to prevent constraint violation completely. As increasing safety zone sizes, also leads to a more restricted workspace, a higher virtual stiffness should be chosen instead.

The presented findings extend the knowledge base for evidence-based selection rules of haptic assistance strategies for teleoperated cooperative robotic systems [12-17]. This knowledge base is yet to be extended for other types of cooperative robotic systems (hands-on, handheld robots), other types of interaction strategies (e.g. gesture control, voice control) and other aspects of human-machine cooperation (e.g. flexible task distribution, shifting degrees of autonomy, arbitration).

Applying selection rules from the abstracted knowledge base to real life surgical applications requires the systematic characterisation of sensorimotor tasks from surgical workflows and the definition of standardized assistance profiles, to be matched with task requirements accordingly. For this purpose, we propose model-based cooperative robotic assistance design where surgical workflow knowledge on the one side and human-robot cooperation models on the other are integrated to support evidence-based decision making during early phases of the development process.

5 Conclusion

The study shows that volumetric haptic assistance can provide usability benefits for navigation tasks common in orthopedic and neurosurgical use cases, like preparing implant fits and preserving sensitive tissues. These results can be integrated in a knowledge base for selection rules for haptic assistance in surgical applications, which in future can be the basis for the development of assistance profiles. In the future such profiles could be matched with surgical task requirements to support evidence-based decision making during early-stage medical device development.

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