Interacting with Deformable User Interfaces: Effect of Material Stiffness and Type of Deformation Gesture

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Abstract. Deformable User Interfaces (DUIs) are increasingly being proposed for new tangible and organic interaction metaphors and techniques. To design DUIs, it is necessary to understand how deforming different materials manually using different gestures affects performance and user experience. In the study reported in this paper, three DUIs made of deformable materials with different levels of stiffness were used in navigation tasks that required bending and twisting the interfaces. Discrete and continuous deformation gestures were used in each case. Results showed that the stiffness of the material and the type of gesture affected performance and user experience in complex ways, but with a pervading pattern: using discrete gestures in very short navigation distances and continuous gestures otherwise, plus using lower-stiffness materials in every case, was beneficial in terms of performance and user experience.

Keywords: deformable, organic, tangible, user interface, force, bend, twist, zoom, scroll, stiffness, gesture, discrete, continuous, performance, UX.

1 Introduction

Deformable User Interfaces (DUIs) lie in the intersection between Organic User Interfaces (OUIs) [1] and Tangible User Interfaces (TUIs) [2]. They consist of physical objects that are intended to be grasped and manipulated with the hands in order to interact with a system. The manipulation of a DUI results in the physical deformation of the material the object is made of. Thus, deforming the interface elastically or plastically is the distinctive form of input to the system when using a DUI. Such deformations are designed to give physical form to the interaction with information.

Functional deformable prototypes that implement deformation interactions as they have been envisioned are still difficult to build. Examples include crumpling and restoring a display [3], and new device concepts that are heavily based on new nanotechnological sensors and materials [4, 5]. Meanwhile, HCI is advancing based on *ad-hoc* DUI prototypes with targeted functionality [6-10], or non-functional prototypes used in qualitative studies [3]. DUIs can come in very different sizes and shapes. In the literature, we find that paper-inspired DUIs [3, 6-8] have received most of the attention. Examples of alternative approaches include the manipulation of raw material [9, 10]. In all of them, a common integral part of the interaction is that the user exerts forces on the interface, causing deformation of the material.

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Many such deformation gestures have been proposed in earlier work. However, the impact that the physical characteristics of different deformable materials have on the execution of these gestures has not been studied systematically. Only Lee *et al.* [3] compared deformation gestures with interfaces made of different materials, but their prototypes were non-functional and the interactions imaginary. To address this gap, in this paper we report a study that takes a first look at the stiffness of a deformable material as a design parameter. In particular, we investigate how material stiffness affects performance and user experience when performing whole-device deformations in navigation tasks (twisting to scroll and bending to zoom), using either discrete or continuous gestures. Three functional DUIs were used, which were identical in their smartphone-like form factor but different in the stiffness of the material they were made of. With this study, we address part of the research agenda proposed in [11].

2 Research Study

2.1 Deformable Hardware

We built a family of functional DUI research prototypes (called *Kinetic DUI-RP*) [11], which could be bent and twisted using both hands. Each prototype consisted of two rigid parts joined by a 62mm-long central body made of deformable material. The rigid parts afforded holding the device and exerting torque actions. Each research prototype (RP) contained a set of deformation sensors (strain gauges) that could detect bending and twisting of the deformable body with 10-bit accuracy and 200Hz sample rates. In this study, three Kinetic DUI-RP interfaces were employed, which were built using different deformable materials in the central section. The deformable material in each prototype presented a different rotational stiffness, and consequently different amount of force was required from a user to bend and twist each prototype. The three prototypes could detect bend and twist deformations of up to 25 degrees away from the resting flat position (Fig. 1). As the Kinetic DUI-RPs did not include a visual display, they were connected to an external computer display.

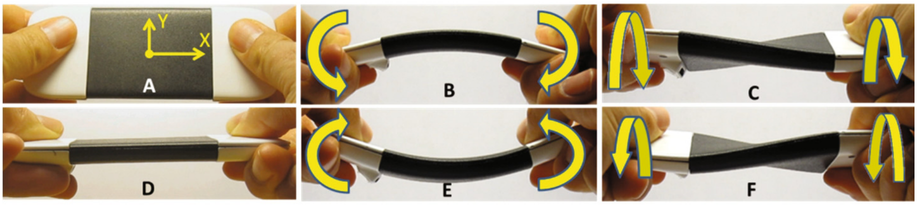

Fig. 1. Main axes of a Kinetic DUI-RP (A). Bend up gesture (B). Twist down gesture (C). Resting position (D). Bend down gesture (E). Twist up gesture (F).

2.2 Experimental Design

An experiment was designed in which navigation through schematic information spaces was performed by bending or twisting the prototypes. Two independent variables (IVs) were selected: stiffness of deformable body and type of gesture.

Navigation Task. We devised a one-dimensional navigation task for each deformation gesture: zooming for bending, and list-scrolling for twisting. These tasks were chosen for being intuitive according to taxonomies [3, 8] and to our own pilot research. From an interaction perspective, both tasks were implemented to be equivalent in every other respect. The GUIs showed schematic representations of the information spaces, as shown in Fig. 2. In both cases, the space was divided into 12 zones (concentric rectangles for zooming, and stacked horizontal slots for scrolling). The position of a red cursor (a thin rectangle or a horizontal line) was controlled by the user. When the cursor entered the area of the target, this was highlighted with the target zone changing its color. If the cursor remained within the target continuously for 2 seconds (*dwell* selection), the task was complete.

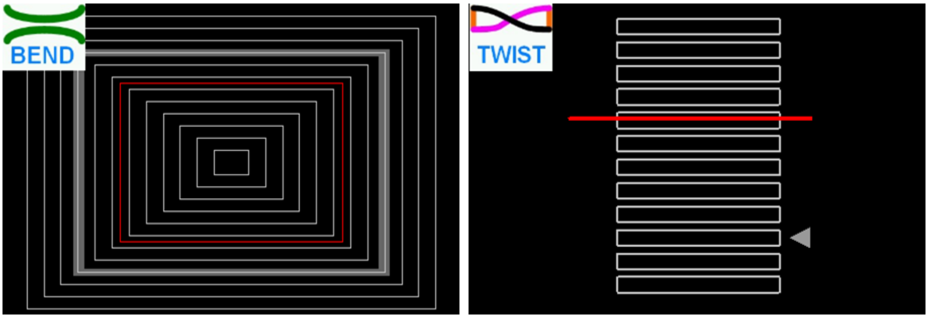

Fig. 2. GUI representations for bend-to-zoom (left) and twist-to-scroll (right)

Stiffness of the Deformable Material. The three levels of stiffness selected (measured as rotational stiffness, in *N·m/rad*), were: 2.5 (highest stiffness), 1.3 (medium stiffness), and 0.45 (lowest stiffness). All three values are well below the threshold of perception of rigidity [12], meaning that even the most rigid of these interfaces felt clearly deformable when manipulated. In addition, the differences between them were well above JNDs [13], thus being clearly discriminable from each other when manipulated.

Type of Deformation Gesture. Two types of deformation gestures were compared: *continuous* and *discrete*. When using continuous gestures, bending or twisting the device beyond a threshold angle (4.5 degrees) started to displace the cursor. In bend-to-zoom, the rectangular cursor changed in size: bend up/down to zoom in/out (Fig. 1, B and E). Similarly, in twist-to-scroll the cursor line displaced vertically: twist up/down to scroll up/down (Fig. 1, F and C). The speed of displacement of the cursor was proportional to the amount that the interface was deformed beyond the threshold. A broad range of speeds could be attained in this way, between 0.02 and 8.6 zones/s.

Discrete gestures, on the contrary, were performed in a “deform-and-restore” fashion. The GUI representation and the direction of the mappings were the same. However, every time a discrete gesture was performed, the cursor displaced instantaneously by one full position. The action was triggered when the deformation surpassed a threshold angle of 10 degrees. To trigger another step, the interface had to be restored to its resting position and then deformed again. Thus, the speed of the navigation depended on the frequency at which deform-and-restore cycles were performed.

Experimental Procedure. A 2-way (2x3) repeated-measures experiment was designed. The IVs were the *rotational stiffness* of the device (*High*, *Medium* and *Low*), and the *type of deformation gesture* (*Discrete* and *Continuous*). In each of the six conditions, 40 repetitions of a navigation task were presented in random order, 20 repetitions requiring the use of bend to zoom, and the other 20 using twist to scroll. Of the 20 repetitions of each navigation task, half (10) started with the cursor located at each end of the navigation space (at the outermost/innermost rectangle for zooming, or at the topmost/bottommost slot for scrolling). The target could be located at 10 different distances, between 1 and 10 positions away. Thus, the target was never located at the very end of the navigation space. This was done to preserve the possibility of overshooting the target in every repetition As a result, the strategy of navigating at maximum speed to the other end was impractical. A label and a graphic representation of that gesture were displayed on the top-left corner of the GUI. This eased the mental demand of identifying the gesture to be used in each new task (Fig. 2).

Twelve participants were recruited for this study: 8 male (1 left handed); 4 female (2 left-handed); aged 27-42 (M=35; SD= 5.5). The order of presentation of the conditions was counterbalanced as follows: six participants completed the three conditions with continuous gestures first, and then the three conditions with discrete gestures (counterbalancing the order in each case). The other six participants completed the conditions in the inverse order. No time limit was imposed for the completion of each task. Each condition was followed by filling in a standard NASA-TLX questionnaire [14] with an additional *preference* category. Each session ended with a brief semi-structured interview to further assess the UX.

3 Results

3.1 Performance

The normalized time (NT) to reach the target (i.e. the time per unit of distance to the target) was selected as a measure of the performance across different conditions. The total time used to calculate NT started to be counted when the threshold of displacement was first surpassed, i.e. when the cursor started to displace for the first time. The 2 seconds of dwell time at the end of the task were not included as part of the total time. Thus, the task was timed until the cursor entered the area of the target for the last time before a successful dwell selection.

A two-way repeated-measures ANOVA test was conducted to analyze NT. It was found that both the rotational stiffness of the device [$F(2,22)=12.53$, $p<0.001$] and the type of gesture [$F(1,11)=77.63$, $p\approx0$] had statistically significant effects on NT (Fig. 3), with no significant interactions between the IVs [$F(2,22)=0.43$, $p=0.66$].

Looking into each IV, NT increased significantly with the stiffest material (Fig. 3, left). Post-hoc analysis (Fischer's $LSD_{95\%}$[1] = 0.037) showed that the significant differences were observed between the material with high stiffness (M=0.365s; SD=0.11) and both the material with medium (M=0.323s; SD=0.118) and with low stiffness (M=0.301s; SD=0.104), with no significant difference between the last two. Regarding the type of gesture (Fig. 3, right), NT was significantly higher (less efficient) with continuous gestures (M=0.412s; SD=0.097) than with discrete gestures (M=0.253s; SD=0.055).

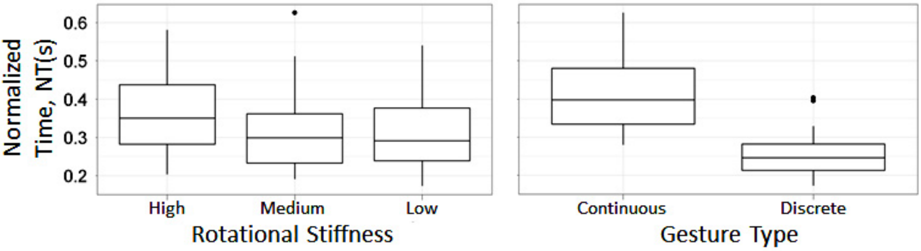

Fig. 3. Average normalized time, NT (time per unit of distance) for different levels of rotational stiffness (left) and gesture types (right)

Further analysis of the data regarding the effect of the gesture type revealed that this effect was more complex than just described. Fig. 4 shows NT graphically represented as a function of the initial distance to the target. Separate graphs are shown for bend-to-zoom and for twist-to-scroll tasks. In both cases, it can be observed that for short navigation distances discrete gestures were more efficient than continuous ones, and this is the dominant effect in the ANOVA (Fig. 3, right). However, for longer distances, continuous gestures became more efficient. Approximate cutting distances for the more efficient gesture type were found to be: 8 distance units for bending and 4 distance units for twisting (see crossing points for the Local Polynomial Regression Fitting – Loess – trend curves in Fig. 4).

Also in Fig. 4 it can be seen that, for discrete gestures, there was no apparent difference between bending and twisting for the behavior of TM over the distances to target. Instead, the difference in TM was most acute for continuous gestures and short navigation distances. In such cases, navigation by bending was far less efficient than navigating by twisting. These observations suggest that initiating, stopping and inverting input torques is done more easily when twisting the device than when bending it. Consequently, this difference becomes apparent in short distance navigations, where the initiation and termination of the navigation accounts for a bigger fraction of the complete navigation process. A hypothesis to explain this difference is that it may be easier to exert pairs of forces around some axes of the prototype than others. Holding the device with both hands as shown in Fig. 1 allowed twisting the interface up and down without changing the way it was held: the length of the thumb resting above and the fingers aligned below could easily redistribute forces to create pairs with enough arm distance in either direction around the *X* axis (Fig. 1, A), without having to

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[1] Fischer's Least Significant Difference.

change the position of the thumb or the fingers. To bend the prototype, however, the same way of holding it offered no arm distance to produce pairs of forces around its Y axis in such an easy way. In fact, a tendency was observed to reposition the fingers to bend up (the thumbs moved apart towards the edge and the fingers pushed from below) or to bend down (the fingers moved towards the edge and the thumb pushed from above). In addition, bigger dispersion in the data was observed when using continuous gestures in bending tasks, suggesting that participants employed a larger variety of procedures to bend than to twist with continuous gestures. Further research will help understand better these interesting ergonomic aspects of the interaction.

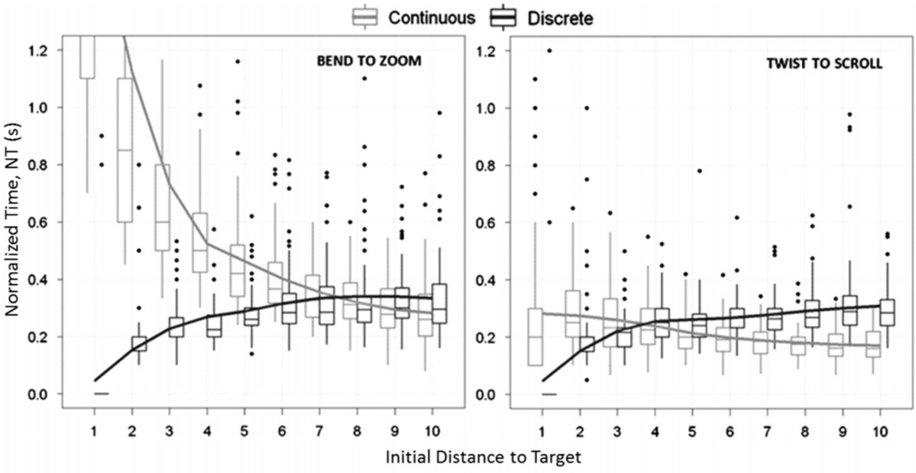

Fig. 4. NT as a function of the initial distance to the target. *Left:* bend-to-zoom. *Right* twist-to-scroll. Trends are shown by Local Polynomial Regression Fitting (Loess) curves.

3.2 Subjective Workload

NASA Task Load Index (TLX) [14] was used to assess quantitatively the relative subjective workload between conditions. For each condition, participants provided ratings on the 20-point scales of the six TLX questionnaire categories: *mental demand*, *physical demand*, *temporal demand*, *performance*, *effort*, and *frustration*. From these ratings, the overall subjective task load index (TLX) was calculated for each condition. Fig. 5 shows these results graphically. These results were analyzed calculating 2-way repeated-measures ANOVAs for the index and for each sub-category.

The outcome of this analysis is summarized in Table 1. The main finding regarding subjective workload was that none of the IVs had a statistically significant main effect on the overall TLX index. This analysis did, however, reveal some statistically significant main effects from both IVs on several of the sub-categories. It particular, the medium-stiffness prototype led to significantly lower levels of *mental demand*, as well as to higher levels of *performance* when compared to the other two prototypes. Regarding the effect of the type of gesture, discrete gestures led to significantly higher levels of *physical demand*, *time pressure* and *effort expended.*

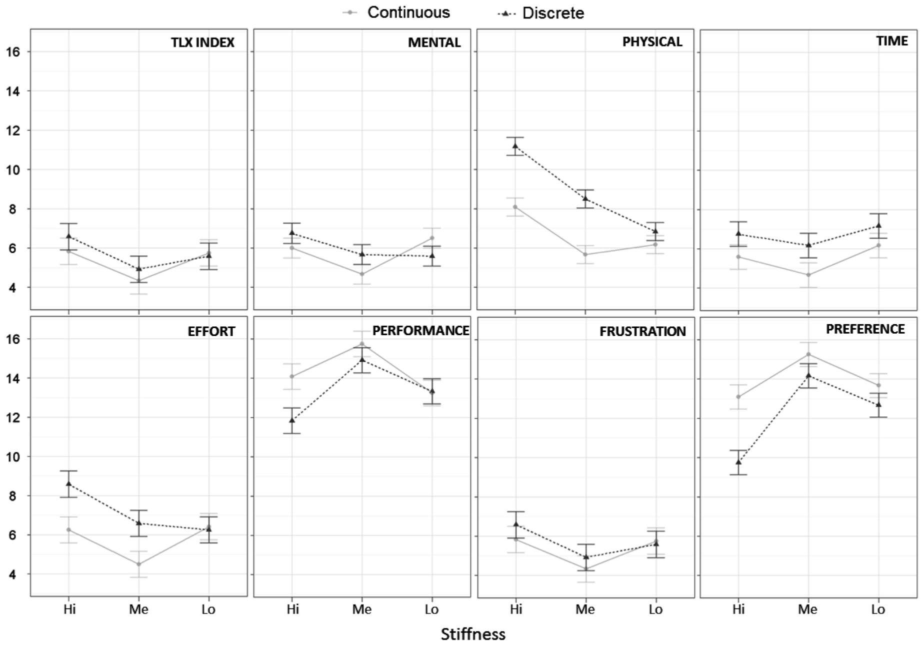

Fig. 5. Summary of NASA-TLX plus preference rating results, including interactions between independent variables. Low values are more positive, except in *Performance* and *Preference*. The error bars represent Fischer's LSD, 95% (overlapping bars are not significantly different in *post-hoc* analysis, 95%).

Table 1. Summary of the 2-way ANOVA analyses conducted for the TLX index and for its sub-categories, plus a *Preference* scale (*p* values corrected for sphericity using Huynh-Feldt). Levels of significance of at least 95% and 99% are indicated by * and ** respectively.

	Stiffness		Gesture Type		Interaction b/t IVs	
	F(2,22)	p	F(1,11)	p	F(2,22)	p
TLX	2.85	0.103	3.06	0.108	**4.65**	**0.01 ****
Mental	**4.68**	**0.02 ***	0.34	0.572	**4.53**	**0.036***
Physical	3.75	0.056	**6.82**	**0.024***	**9.03**	**0.005****
Time	1.18	0.316	**6.15**	**0.031***	0.18	0.765
Effort	1.38	0.27	**4.8**	**0.05 ***	**4.56**	**0.022***
Performance	**4.16**	**0.043***	1.12	0.313	**3.55**	**0.046***
Frustration	1.99	0.16	0.17	0.687	0.56	0.57
Preference	**4.80**	**0.02 ***	**5.79**	**0.035***	**5.00**	**0.017***

The interactions between IVs were statistically significant for the TLX index and for all the sub-categories except *time pressure* and *frustration* (Table 1). Fig. 5 represents these interactions graphically. The origin of the significant interactions in the *TLX index* itself as well as in *effort expended* and *physical demand* was that ratings were more positive with continuous gestures when using high- and medium-stiffness prototypes, but there was no difference between gesture types when using the low-stiffness prototype. The interaction between IVs for the *performance* category had a similar origin, with the difference that ratings were approximately equal with medium and low-stiffness. In all these cases, it was beneficial to use continuous gestures with higher-stiffness prototypes, but the gesture type made no difference when using the lowest-stiffness prototype. In other words, the low-stiffness deformable prototype stood out for being more gesture-type agnostic. In a similar trend, the *mental demand* category presented the singularity that ratings using continuous gestures were more positive (lower) only when using the medium-stiffness RP, but no differences due to the type of gesture were observed with the other two materials.

3.3 User Experience

The subjective user experience was assessed through a quantitative measure of relative preference between conditions, and via semi-structured interviews.

Each NASA-TLX questionnaire was appended with an additional category, called *overall preference*. This category was entirely independent from the TLX method, and was not used for the calculation of the index. Instead, it was a separate scale that the participants also rated at the end of each condition, together with the rest of the NASA-TLX scales, so as to keep the process of evaluation as simple, homogeneous and straight-forward as possible. A two-way, repeated-measures ANOVA test was also performed on these results (see last row in Table 1, and bottom-right graph in Fig. 5). This analysis revealed that both IVs affected the ratings of overall preference statistically significantly. Continuous gestures were preferred over discrete ones, and both medium and low stiffness were preferred over high stiffness in the deformable material. The interaction between the IVs was also significant. The interaction behavior was similar to that observed for *Performance* ratings: continuous gestures were strongly preferred over discrete ones when using the stiffest prototype, but there was no significant gesture preference when using any of the other two materials.

At the end of each experimental session, after all conditions had been conducted, participants were interviewed regarding the user experience in the different experimental conditions. During this interview, participants were asked to choose a single stiffness and type of deformation gesture as their absolute preferred ones. As shown in Fig. 6, medium and low stiffness were equally preferred over high stiffness, and continuous gestures were clearly preferred over discrete ones.

Other comments from the interviews offered further insight into these results. High stiffness was considered good for beginner level, but tiring and laborious, particularly with discrete gestures. Discrete gestures were best performed with medium and low stiffness. The lowest stiffness was pleasant in the hands and it felt very responsive, but it was sometimes described as too sensitive to control with continuous gestures. Some participants commented that discrete gestures were best for short distances and continuous gestures for long distances, just as observed in the performance results.

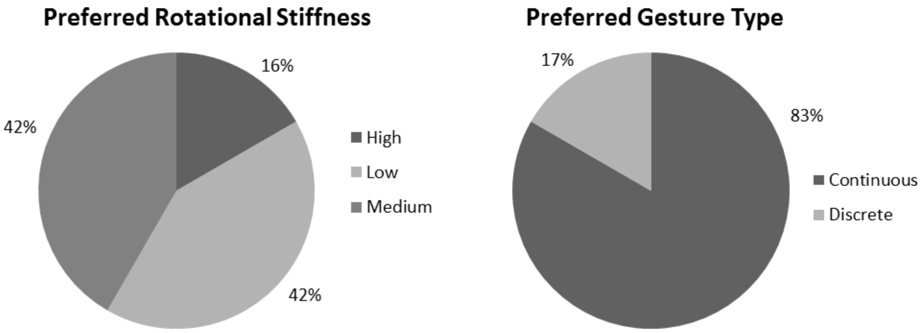

Fig. 6. Preferred rotational stiffness and type of gesture, as selected during the interviews

4 Discussion and Conclusions

The results from this study are valid within the boundaries of the design decisions adopted in the setup: form factor, range of stiffness of the deformable material, navigation tasks by bending and twisting, and discrete/continuous deformation gestures. These were informed design decisions (based on prior literature and on our own iterative piloting) made to encompass a broad and relevant set of use scenarios for current and future DUI design efforts.

For the design space covered in this study, the results showed that the stiffness of the deformable material and the type of deformation gesture had significant effects both on the performance and on the user experience when completing navigation tasks. These variables presented multiple interactions in the quantitative subjective workload and preference measures utilized. Further mining of the results showed that the ergonomics of producing different rotational deformation gestures (namely bending and twisting) modulated the main results in observable ways, pointing towards additional directions in our research agenda.

The main results obtained in this study are summarized in the following points:

- Performance in navigation tasks was significantly worse when they were executed using the prototype with the stiffest deformable material.
- Overall, performance was significantly better with discrete gestures. However, discrete gestures outscored continuous gestures in performance only in short navigation distances. Beyond 4 to 8 units of distance, continuous gestures led to more efficient performance. Future studies should investigate performance behavior in much longer navigation spaces (common in interfaces such as media collections).
- Differences in performance favoring twisting over bending interactions were observed, which could be attributed to ergonomic differences between these gestures.
- The IVs did not have any significant effect on the overall Task load Index. However, in the subjective workload sub-categories, high and medium stiffness were respectively rated least and most favorably. Continuous gestures were rated equally or more favorably than discrete gestures, but never the other way around. With the low-stiffness DUI, continuous and discrete gestures were always rated equally.

- The high-stiffness DUI was particularly disliked (good only for beginners). The low-stiffness DUI was slightly more difficult to control continuously for some.
- Discrete gestures were considered appropriate only for short navigation distances.

To conclude, this research has shown that designing interactions with DUIs (i.e. interactions that require physically deforming material with the hands) requires understanding how mechanical and ergonomic parameters influence performance and user experience. Even within the limited design space considered here, significant influences and complex interactions were observed.

Future work should further investigate the role that these and other physical parameters play in the successful design of interactions with a larger variety of DUIs.

References

1. Vertegaal, R., Poupyrev, I.: Organic User Interfaces. Commun. ACM 51, 26–30 (2008)
2. Ishii, H.: The tangible user interface and its evolution. Commun. ACM 51, 32–36 (2008)
3. Lee, S.-S., Kim, S., Jin, B., Choi, E., Kim, B., Jia, X., Kim, D.: Lee, K.-p.: How users manipulate deformable displays as input devices. In: CHI 2010, pp. 1647–1656 (2010)
4. Ryhänen, T., Uusitalo, M.A., Ikkala, O., Kärkkäinen, A.: Nanotechnologies for Future Mobile Devices. Cambridge Univ. Pr. (2010)
5. The Morph Concept, Nokia Research Center, vol. 2011 (2011)
6. Wightman, D., Ginn, T., Vertegaal, R.: BendFlip: Examining Input Techniques for Electronic Book Readers with Flexible Form Factors. In: Campos, P., Graham, N., Jorge, J., Nunes, N., Palanque, P., Winckler, M. (eds.) INTERACT 2011, Part III. LNCS, vol. 6948, pp. 117–133. Springer, Heidelberg (2011)
7. Gallant, D.T., Seniuk, A.G., Vertegaal, R.: Towards more paper-like input: flexible input devices for foldable interaction styles. In: UIST 2008 (2008)
8. Schwesig, C., Poupyrev, I., Mori, E.: Gummi: a bendable computer. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (2004)
9. Sheng, J., Balakrishnan, R., Singh, K.: An interface for virtual 3D sculpting via physical proxy. In: Proceedings of the 4th International Conference on Computer Graphics and Interactive Techniques in Australasia and Southeast Asia (2006)
10. Murakami, T., Nakajima, N.: DO-IT: deformable object as input tool for 3-D geometric operation. Computer-Aided Design 32, 5–16 (2000)
11. Kildal, J., Paasovaara, S., Aaltonen, V.: Kinetic Device: Designing Interactions with a Deformable Mobile Interface. In: CHI 2012 (2012)
12. Biggs, S.J., Srinivasan, M.A.: Haptic interfaces. In: Stanney, K.M. (ed.) Handbook of Virtual Environments, pp. 93–116. LEA (2002)
13. Chen, J.: Human haptic interaction with soft objects: discriminability, force control, and contact visualization. Dept. Mech. Eng. PhD in Mechanical Engineering (1996)
14. NASA TLX: Task Load Index (2012), `http://humansystems.arc.nasa.gov/groups/TLX`