Fingertip Tactile Devices for Virtual Object Manipulation and Exploration

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ABSTRACT

One of the main barriers to immersivity during object manipulation in virtual reality is the lack of realistic haptic feedback. Our goal is to convey compelling interactions with virtual objects, such as grasping, squeezing, pressing, lifting, and stroking, without requiring a bulky, world-grounded kinesthetic feedback device (traditional haptics) or the use of predetermined passive objects (haptic retargeting). To achieve this, we use a pair of finger-mounted haptic feedback devices that deform the skin on the fingertips to convey cutaneous force information from object manipulation. We show that users can perceive differences in virtual object weight and that they apply increasing grasp forces when lifting virtual objects as rendered mass is increased. Moreover, we show how naive users perceive changes of a virtual object's physical properties when we use skin deformation to render objects with varying mass, friction, and stiffness. These studies demonstrate that fingertip skin deformation devices can provide a compelling haptic experience appropriate for virtual reality scenarios involving object manipulation.

Author Keywords

Haptics; Virtual Reality; Mass Perception

ACM Classification Keywords

H.5.1 Multimedia Information Systems: Artificial, augmented, and virtual realities; H.5.2 User Interfaces: Haptic I/O

INTRODUCTION

Recent developments in head mounted virtual reality displays have led to dramatic improvement in the quality and accessibility of virtual experiences. These displays enable impressive visual experiences, but advancements in haptic interaction are needed to create a truly immersive experience. Kinesthetic haptic devices (robotic manipulators that generate an external force on the user) enable compelling haptic interaction with virtual worlds, but these devices are restricted to small tabletop workspaces, and require users to interact with the virtual world through a physical tool rather than with their bare hands. There is a need for haptic devices that render compelling force information while allowing direct haptic interaction with virtual environments.

When we manipulate objects in the real world, local forces at the fingertips cause deformation of the skin on the fingerpads, providing information about the objects' physical properties. Mechanorecepters in the skin are capable of sensing both low and high frequency information about force magnitude, direction, and texture [1], [11]. We developed two 3-degree-of-freedom (DoF) fingertip tactile devices to deform the skin on the fingerpads in a manner similar to direct object manipulation. The devices use a novel tether and bias-spring actuation method, along with the well characterized delta mechanism, to allow high fidelity motors and encoders to be mounted longitudinally on the back of the finger, with small size and weight. During a grasp and lift maneuver, the high friction element touching the skin, called the tactor, can move both normally against the fingerpad (as when grasping) and laterally (as when lifting). The ability to render both normal and lateral tactile feedback makes these devices particularly well suited for conveying forces during object manipulation.

Traditionally, researchers have focused on vibration feedback as a tactile solution for conveying force and contact information [12], [14], [23]. While vibration is suitable to convey contact events and texture, it does not directly convey direction and magnitude information, preventing its use as a force substitute. More recently, researchers have investigated tactile devices that apply forces to the fingerpad. When appended to the end of traditional kinesthetic devices, these tactile devices have been shown to increase the perception of virtual stiffness and friction [20], [21], [22], aid in the discrimination of textures during environment exploration [5], and in some cases replace force feedback entirely while preserving performance in teleoperated tasks [17], [24].

The evidence of effective tactile feedback has led researchers to develop haptic devices that allow direct touch with virtual environments. An example of a wearable kinesthetic device is Dexmo [7], which is grounded to the back of the hand and provides force to resist grasping motions. Carter et al. developed a system that uses focused ultrasound to project points of haptic feedback on user hands [2]. Others have developed tactile devices worn on the finger, recreating interaction forces at the fingerpad. Minamizawa et al. used a fingertip moving belt design in conjunction with an Omega.3 haptic device to render virtual mass [15]. Prattichizzo et al. [19] and Perez et al.

CHI 2017, May 6-11, 2017, Denver, CO, USA.

ACM ISBN 978-1-4503-4655-9/17/05 ...$15.00.
http://dx.doi.org/10.1145/3025453.3025744

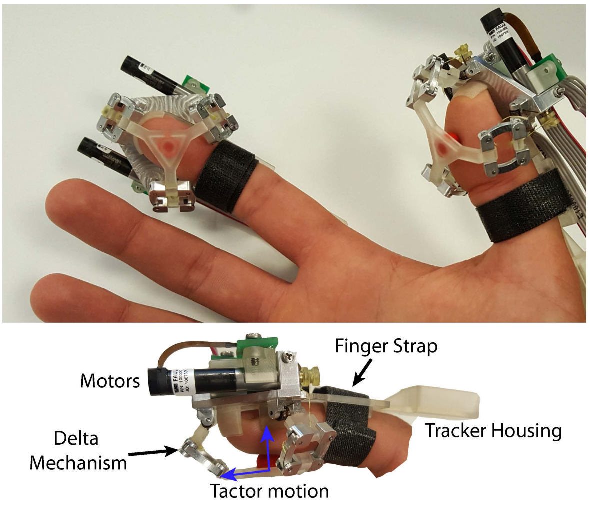

Figure 1. Fingertip devices on the index finger and thumb. Each device tactor can move in 3-DoF against the fingerpad (normally and laterally), with minimal encumberance.

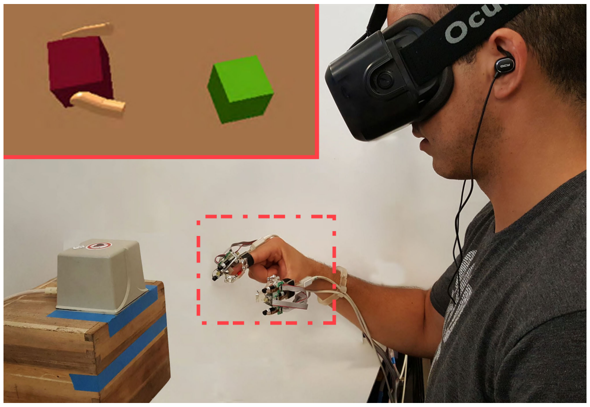

Figure 2. Example of the experimental setup during both experiments. Devices were worn on the index finger and thumb and used to render virtual environment forces while the scene was rendered on an Oculus DK2 display.

[18] developed wearable devices that compress a platform normal to the fingerpad and also change the platform orientation. Leonardis et al. [13] developed a wearable device capable of moving in 3 degrees of freedom that reduced grip forces during virtual lifting when compared to no haptic feedback.

While many tactile devices have been shown to improve performance during specific isolated tasks, the effect of tactile feedback on naive perception of mass, a percept that normally includes a kinesthetic component, needs further investigation. The role of tactile feedback in mass perception is especially important since it has been suggested that humans integrate visual and haptic information in an optimal fashion, minimizing the variance in a final estimate by combining the two senses [4]. While some parameters can be estimated solely through visual feedback, mass requires haptic sensation because vision cannot be used to determine the density of objects. Though tactile feedback for perception of mass has been investigated with the aid of traditional kinesthetic devices or object props [26], [15], [6], to the authors' knowledge, this work is the first direct investigation of virtual mass perception and other object physical properties when using only a finger grounded skin deformation device.

Our new devices have 3 purely translational degrees of freedom, making them particularly well suited for rendering forces that act in multiple directions during object manipulation, such as weight, friction, and stiffness. We performed two user studies to investigate how virtual objects are perceived with fingertip skin deformation feedback. The results show that users can distinguish between virtual objects with different mass, and also how naive user perception of virtual object properties is affected when the mass, stiffness, or friction of the virtual objects is modified.

SYSTEM DESIGN

The fingertip tactile devices (Fig. 1) have two separate components. The first is a finger grounding interface that straps to the medial phalanx. Several sizes of this interface were created to enable use with participants of varying finger size. Grounding to the medial phalanx helps distribute forces from the tactor and results in a stimulus that feels like it originates from an external source. The interface holds a magnetic tracking sensor from an Ascension 3D Guidance trakSTAR system, which provides tracking information about the position and orientation of the fingers in free space at 200 Hz.

The second component of the devices is the delta mechanism, which attaches to the finger grounding interface via a dovetail feature. The delta mechanism moves in 3 DoF with a 10×10×5 mm workspace and has the ability to make and break contact with the fingerpad. It weighs approximately 32 g and is bounded by a box of size 21.5×48.8×40.2 mm. The position of the delta mechanism was controlled using a Sensoray 826 I/O board to output desired motor torques to linear current amplifiers. The bias springs in the base revolute joints provide mechanism torques in one direction, while the Faulhaber 0615 DC motors with 06/1K 64:1 gearboxes spool the tethers attached to the base links to provide torques in the other direction. The delta mechanism is capable of up to 7.5 N of normal force and 2 N of lateral force. CAD models of the entire assembly can be found on https://github.com/sschorr/WearableDevice.

Virtual environments were created using CHAI3D [3], which uses the god-object algorithm [9] for determining dynamic object interaction forces. This algorithm uses a proxy point that is attached to the haptic interaction point (HIP) by a virtual spring (surface stiffness). When the HIP moves within a virtual object, the proxy point is constrained to the object surface, stretching the spring and determining a virtual interaction force. The neutral position of each device tactor was set for each participant by moving the tactor into the fingerpad by approximately 0.5 mm. This initial offset normal to the fingerpad prevents the tactor from slipping laterally across the finger during use. During haptic rendering, the orientation of the devices in free space was used to transform the force vector of the virtual interaction force into the reference frame of the delta mechanism. The device tactors were then com-

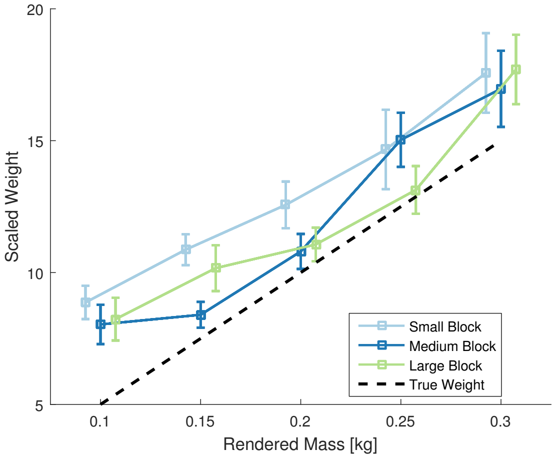

Figure 3. Mean participant response weight for each block mass and size. The true scaled weight is based on the "standard" block with mass 0.2 kg and weight "10". Error bars indicate standard error.

manded to move 2.1 mm/N from the neutral position in the vector direction of the virtual environment interaction forces, based on the mean lateral stiffness of the fingerpad [16]. The virtual environment and resulting interaction forces were updated at approximately 3 kHz with overall system latency of approximately 20-30 ms from user input motion to visuohaptic rendering, the majority from tracker delay. An Oculus DK2 was used to display the virtual environment to users. Participants wore noise canceling headphones playing white noise during the experiments. The system setup is shown in Fig. 2.

MASS PERCEPTION STUDY

The objective of this experiment was to determine how virtual object mass and size affected weight perception of device users. Six participants, five with engineering backgrounds, completed the experiment after giving informed consent. The experimental procedure was approved by Stanford University's Institutional Review Board.

Methods

Participants evaluated the weight of virtual blocks with heights of 50, 100, or 150 mm and masses of 100, 150, 200, 250, or 300 g. Blocks were presented in pairs where the first was always the "standard" block (100 mm tall and 200 g). Participants were asked to grasp the block between the index finger and thumb and lift it approximately 15 cm. They were then told that the standard block has a weight of "10" and were presented with one of the alternative blocks. Participants were asked to evaluate its weight with a number relative to the 10 of the standard block, using a magnitude estimation scale. Each combination of block size and weight was presented 5 times for a total of 75 trials per participant.

Results

Mean participant response weight for each mass and block size is indicated in Fig. 3. Participant perceived weight increased with increasing block mass for all block sizes. Fig. 4 shows the mean grip force per rendered mass. Participants used increased grip force to lift the blocks as the rendered mass was increased.

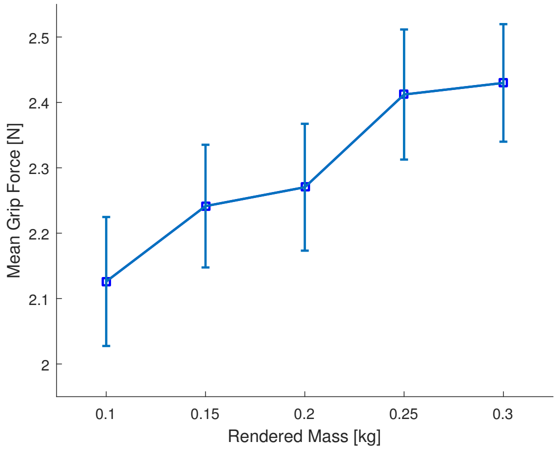

Figure 4. Mean grip force for each rendered mass. Error bars indicate standard error.

We fit a linear mixed-effects model via maximum-likelihood to the response variables of evaluated weight and grip force. Block mass and size were included as fixed-effects terms and differences in participant performance were included as a random-effect term. An ANOVA test to determine if coefficients representing the fixed-effects terms were equal to 0 indicated that block mass had a significant effect on perceived weight and mean grip force ($F_{1,447} = 156.3, p < 0.001$ and $F_{1,447} = 13.56, p < 0.001$, respectively). The effect of block size on perceived weight and grip force was not statistically significant.

Discussion

The statistically significant effect of rendered mass on participant perceived weight indicates that participants were able to use the tactile devices to discriminate between virtual objects of varying mass. While participants perceived the masses as having a narrower weight range than previous real world experiments [10], the weight range reported with the devices actually more closely matches the true scaled weight. When lifting an object, the resulting force vector on the finger is determined both by the normal force associated with the grasping of the object, and the gravity force during the lift. Participants were able to parse the force vector rendered by tactile feedback and interpret the component representing the object weight.

We did not see a strong effect of the size-weight illusion [25] that has previously been shown with objects of varying size. This phenomenon has been shown to work in virtual reality with both real objects [10] and kinesthetic haptic devices [8]. In our experiment, the smallest block had the highest mean reported weight across all masses, but there was no statistically significant effect of block size on perceived weight. It could be that the lack of kinesthetic resistance during the lifting motion, which would result in different lifting accelerations for each mass given a specific lift force, prevented the manifestation of the illusion. Further research is needed to determine whether the effect can occur with purely tactile feedback.

Cutaneous sensory information is known to be critical for skilled grasping [27], and the increase in mean grip force with increasing rendered mass shows that participants were modifying their grip based on the real-time estimation of the object mass. When lifting objects in the real world, grip force is typically regulated to prevent object slipping. The devices' ability to provide information about normal grasping force and object mass allowed users to modulate grip force based on the mass of the object being lifted.

PHYSICAL PROPERTIES STUDY

The previous study required that users consider the haptic stimulus they received as mass. We now investigate how the manipulation of various virtual object properties affects perception when naive users are free to manipulate objects in an unprompted manner. Six participants, different from those in the previous study and with no previous experience using skin deformation devices, completed the experiment after giving informed consent. Five of the six participants had engineering backgrounds. The experimental procedure was approved by Stanford University's Institutional Review Board.

Experiment Procedure

In this experiment, participants were presented with a virtual environment consisting of two small blocks on a table. Both blocks had the same size and shape, but were different colors to make them easily distinguishable. Each pair of blocks presented to the participants had matching physical properties with the exception of one varying property: mass (50 g vs. 250 g), stiffness (60 N/m vs. 180 N/m), or friction coefficient between the user's virtual finger and object ($\mu = 0.5$ vs. $\mu = 4$). The experiment participants had no prior knowledge of the virtual parameters being investigated and were only told to freely manipulate the two blocks on the table and describe any noticeable differences between their physical properties. Participants were not time restricted and were allowed to continue until they felt they had adequately described the differences, usually 5-10 minutes. Each participant explored all 3 varying properties in a Balanced Latin Squares order.

Results

Fig. 5 describes the relationship between the physical parameter that was changed and the perceived parameter changes reported by the participants. When the virtually rendered mass was changed, 5 of the 6 participants reported a difference in perceived mass, 3 reported a difference in stiffness, and 1 reported a difference in friction. When the rendered stiffness was changed, 4 participants reported a change in mass, 3 reported a change in stiffness, and 3 reported a change in friction. Finally, when the rendered friction was changed, 2 participants reported a change in mass and 6 reported a change in friction. Importantly, when participants correctly identified the parameter being changed, they always correctly identified which block had the higher and lower values.

Discussion

While many participants perceived a change in the direct physical parameter being modified in the study, many of them also perceived changes in other physical parameters that were not modified. Knowledge of these crossovers in object property perception helps developers avoid unintentionally undermining the intended rendering effects.

		Perceived Change		
		mass	stiffness	friction
Virtual Rendered Change	mass	5/6	3/6	1/6
	stiffness	4/6	3/6	3/6
	friction	2/6	0/6	6/6

Figure 5. Fraction of participants that responded with a perceived parameter change based on the virtually rendered parameter changes. Participants' responses were unprompted, and some responded with multiple perceived changes for the single rendered change.

Most notably, 4 of the 6 participants responded that increasing the object stiffness made the object feel heavier. When questioned further about this observation, some said that they thought the stiffer block was heavier due to the increased forces they felt while holding it. Without an underlying kinesthetic force on the fingerpads, the additional feedback of the resulting from the object's higher stiffness was perceived to be increased force from weight. The dual of this effect was also observed, as 3 of the 6 participants perceived a change in stiffness when the mass of the virtual block was altered. Again, it is likely that participants exhibiting this crossover perceived increased or decreased intensity on the fingerpads rather than directly evaluating the vector directions of the stimulus they felt – normal to the fingerpads for stiffness, and downwards with gravity for mass.

All of the participants recognized altered friction properties of the surface, many specifically using words like "slippery" or "sticky". The effective rendering and perception of frictional forces is critical for modulating interaction forces during manipulation. This likely contributed to the significant effect of object mass on grip force in the previous study.

CONCLUSIONS

We developed fingertip tactile devices to investigate how cutaneous skin deformation could contribute to a compelling, immersive haptics experience for virtual reality without the bulk of traditional kinesthetic haptic devices. We showed that participants are not only able to perceive variations in the weight of virtual objects, but also to modulate their grip force commensurate with the mass of the object being manipulated. Furthermore, we show how changing various physical properties of virtual objects affects completely naive user perception during device use. While users often directly perceive the altered virtual property, there are also frequent situations in which users perceive a different altered characteristic. With the knowledge obtained from these studies, we can create haptically interactive virtual environments with a better understanding of the relationship between rendered and perceived virtual object properties.

REFERENCES

1. I. Birznieks, P. Jenmalm, A. W. Goodwin, and R. S. Johansson. 2001. Encoding of Direction of Fingertip Forces by Human Tactile Afferents. *The Journal of Neuroscience* 21, 20 (2001), 8222–8237.
2. T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *ACM Symposium on User Interface Software and Technology*. 505–514.
3. F. Conti, F. Barbagli, D. Morris, and C. Sewell. 2005. CHAI3D: An open-source library for the rapid development of haptic scenes. In *IEEE World Haptics Conference*. 21–29.
4. M. O. Ernst and M. S. Banks. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 415, 6870 (2002), 429–433.
5. M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli. 2016. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. In *IEEE Haptics Symposium*. 140–146.
6. A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. LÃl'cuyer. 2016. HapTip: Displaying Haptic Shear Forces at the Fingertips for Multi-Finger Interaction in Virtual Environments. *Frontiers in ICT* 3 (2016), 6.
7. X. Gu, Y. Zhang, W. Sun, Y. Bian, D. Zhou, and P. O. Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Conference on Human Factors in Computing Systems*. 1991–1995.
8. M. Hara, C. Asada, T. Higuchi, and T. Yabuta. 2004. Perceptual illusion in virtual reality using haptic interface. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 3901–3906.
9. W. S. Harwin and N. Melder. 2002. Improved haptic rendering for multi-finger manipulation using friction cone based god-objects. In *Eurohaptics Conference*.
10. E. Heineken and F. P. Schulte. 2007. Seeing size and feeling weight: The size-weight illusion in natural and virtual reality. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 49, 1 (2007), 136–144.
11. K. O. Johnson. 2001. The roles and functions of cutaneous mechanoreceptors. *Current Opinion in Neurobiology* 11, 4 (2001), 455 – 461.
12. K.J. Kuchenbecker, J. Fiene, and G. Niemeyer. 2006. Improving contact realism through event-based haptic feedback. *IEEE Transactions on Visualization and Computer Graphics* 12, 2 (2006), 219–230.
13. D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli. 2015. A wearable fingertip haptic device with 3 DoF asymmetric 3-RSR kinematics. In *IEEE World Haptics Conference*. 388–393.
14. W. McMahan, J. Gewirtz, D. Standish, P. Martin, J.A. Kunkel, M. Lilavois, A. Wedmid, D. I. Lee, and K. J. Kuchenbecker. 2011. Tool contact acceleration feedback for telerobotic surgery. *IEEE Transactions on Haptics* 4, 3 (2011), 210 –220.
15. Kouta Minamizawa, Domenico Prattichizzo, and Susumu Tachi. 2010. Simplified design of haptic display by extending one-point kinesthetic feedback to multipoint tactile feedback. In *IEEE Haptics Symposium*. 257–260.
16. N. Nakazawa, R. Ikeura, and H. Inooka. 2000. Characteristics of human fingertips in the shearing direction. *Biological Cybernetics* 82, 3 (2000), 207–214.
17. C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker. 2016. Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery. *IEEE Transactions on Biomedical Engineering* 63, 2 (2016), 278–287.
18. A. G. Perez, D. Lobo, F. Chinello, G. Cirio, M. Malvezzi, J. S. Martín, D. Prattichizzo, and M. A. Otaduy. 2015. Soft finger tactile rendering for wearable haptics. In *IEEE World Haptics Conference*. 327–332.
19. D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi. 2013. Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback. *IEEE Transactions on Haptics* 6, 4 (2013), 506–516.
20. W. R. Provancher and N. D. Sylvester. 2009. Fingerpad skin stretch increases the perception of virtual friction. *IEEE Transactions on Haptics* 2, 4 (2009), 212–223.
21. Z. F. Quek, S. B. Schorr, I. Nisky, A. M. Okamura, and W. R. Provancher. 2014. Sensory substitution using 3-degree-of-freedom tangential and normal skin deformation feedback. In *IEEE Haptics Symposium*. 27–33.
22. Z. F. Quek, S. B. Schorr, I. Nisky, W. R. Provancher, and A. M. Okamura. 2015. Sensory substitution and augmentation using 3-degree-of-freedom skin deformation feedback. *IEEE Transactions on Haptics* 8, 2 (2015), 209–221.
23. R. E. Schoonmaker and C. G. L. Cao. 2006. Vibrotactile force feedback system for minimally invasive surgical procedures. In *IEEE International Conference on Systems, Man and Cybernetics*. 2464 –2469.
24. S. B. Schorr, Z. F. Quek, I. Nisky, W. R. Provancher, and A. M. Okamura. 2015. Tactor-induced skin stretch as a sensory substitution method in teleoperated palpation. *IEEE Transactions on Human-Machine Systems* 45, 6 (2015), 714–726.
25. L. Sjöberg. 1969. Sensation scales in the size weight illusion. *Scandinavian Journal of Psychology* 10, 1 (1969), 109–112.
26. J. M. Suchoski, A. Barron, C. Wu, Z. F. Quek, S. Keller, and A. M. Okamura. 2016. Comparison of kinesthetic and skin deformation feedback for mass rendering. In *IEEE International Conference on Robotics and Automation*. 4030–4035.
27. A. G. Witney, A. Wing, J.L. Thonnard, and A. M. Smith. 2004. The cutaneous contribution to adaptive precision grip. *Trends in Neurosciences* 27, 10 (2004), 637–643.