Exp Brain Res (1999) 128:69–75

RESEARCH NOTE

J. Randall Flanagan · Lorna S. Jakobson
Kevin G. Munhall

Anticipatory grip adjustments are observed in both goal-directed movements and movement tics in an individual with Tourette's syndrome

10 August 1998 / Accepted: 29 January 1999

Abstract We examined grip force adjustments during movements of a hand-held object in a young man (BF) with Tourette's syndrome. We directly compared BF's voluntary up and down movements with tics in the same directions. Movement tics were elicited by cueing BF to move either up or down on a GO signal which appeared after a variable delay. During the delay period, we observed frequent tics which were almost always in the cued movement direction. BF's voluntary movements were well coordinated and featured precise and appropriate anticipatory grip force adjustments such that grip force was modulated in phase with movement-induced fluctuations in load. Precise anticipatory grip force adjustments were also observed in all of BF's movement tics. These results support the hypothesis that tics in Tourette's syndrome are purposeful voluntary movements that are well organized and coordinated.

Key words Tourette's syndrome · Grip force control · Movement tics · Anticipatory control · Arm movement · Grasping

Introduction

Tics are abnormal movements, ranging from simple, clonic muscle contractions to complex, coordinated movements (Jankovic 1997). They are most commonly seen in the context of Tourette's syndrome (TS), named for Gilles de la Tourette, who, in 1885, described nine patients all of whom presented with brief "involuntary" movements.

Many current writers continue to emphasize the "involuntary" nature of tics (Jankovic and Fahn 1986; Lees 1985; Shapiro et al. 1988), and observations that both motor and phonic tics occur even during sleep (Glaze et al. 1983; Jankovic and Rohaidy 1987) seem to support this view. Nonetheless, it has recently been suggested that this characterization of tic behaviours may need to be re-evaluated. Several authors have proposed that many tics are better thought of as "intentional, involuntary actions", meaning that they are purposefully executed, but made in response to an uncontrollable urge (Jankovic 1997; Lang 1991). Others have suggested that new tics (especially complex ones) may go through a process of "evolution" – starting out as purposeful acts that cannot be suppressed (except for brief periods) and gradually becoming more "automatic" or "involuntary" with repetition. This argument has been used to explain changes over time in the production of complex "signing tics" seen in a patient as she acquired proficiency in manual sign language (Lang et al. 1993). Early on, her signing tics were meaningful and related to what she was thinking, feeling, or attempting to communicate, but later on they seemed to lose their purposefulness and were sometimes incompletely produced. Moreover, these later tics often appeared to be triggered "automatically" by certain words and, once triggered, were very difficult to stop, sometimes being repeatedly produced for hours on end. Similar patient reports of an inability to inhibit repeated performance of a tic once begun have appeared elsewhere (e.g., Lang 1991).

In discussing their patient with "signing tics", Lang et al. (1993) proposed that during the development of a new tic, limbic modulation of cerebral cortex might produce the consciously perceived, premonitory sensation ("sensory tic") described by many TS sufferers. This sensation produces an irresistible urge to make a particular movement or sound, and many patients liken it to an itch which must be relieved by scratching (Bliss 1980; Lang 1991). As the tic is repeatedly produced, the authors argue that subcortical centres "learn" the motor act and may eventually come to drive the response on their own, resulting in a more automatic, seemingly "involuntary" tic. It has been noted elsewhere, however, that even long-standing, invariant, simple tics can continue to be associated with (or occur in response to) a consciously

J.R. Flanagan (✉) · L.S. Jakobson · K.G. Munhall
Department of Psychology, Queen's University,
Kingston, Canada, K7L 3N6,
e-mail: flanagan@psyc.queensu.ca,
Tel.: +1-613-545-6007, Fax: +1-613-545-2499

perceived, premonitory urge (Lang 1991). The apparently intentional nature of these tics may explain reports of premotor negativity in some patients with simple motor tics (Karp et al. 1996; although see Obeso et al. 1982).

In the present report, we describe the case of a young man with TS who exhibited frequent phonic and motor tics. The aim of this research was to examine the coordination of his tic behaviours, and to compare these so-called "involuntary" movements with similar movements that were produced voluntarily. We focused on the coordination of grip force adjustments made to a hand-held object during the execution of arm movements.

When an object is held with the tips of the index finger and thumb on either side, grip force (or normal force) normal to the contact surfaces allows for the development of frictional forces which prevent slip by counteracting gravitational forces tangential to the contact surfaces. Normal force is finely adjusted so that it is just slightly greater than the minimum required to prevent slip (Johansson and Westling 1984; for recent reviews see Johansson and Cole 1992; Johansson 1996). If the object is moved up and down, inertial or acceleration-dependent forces are induced that cause fluctuations in the tangential force. During voluntary up-down movements, subjects show anticipatory modulation of their normal forces which allows them to compensate for these changes in load force and maintain a stable grasp. This type of anticipatory control is only seen during the execution of voluntary movements, and can be contrasted with reflex-mediated changes in grip force that follow unexpected perturbations of load (Cole and Abbs 1987; Westling and Johansson 1987). Anticipatory adjustments in normal force are also observed in voluntary isometric movements in which forces tangential to the contact surfaces are generated by pulling or pushing a fixed object (Johansson and Westling 1984; Johansson et al. 1992). In the study described below, we looked for evidence of anticipatory modulation of grip forces in our patient with TS during the production of voluntary up-down movements of a hand-held object and during spontaneously produced motor tics involving up and down movements. Evidence of anticipatory grip force modulation during tics would support the conclusion that these movements are intentionally produced at some level. A preliminary report of some of the results presented in this paper has been published in abstract form (Jakobson et al. 1996).

Methods

Participants

We tested a 21-year-old male university student with Tourette's syndrome (TS). This individual, who we will refer to as BF, displayed frequent and varied motor and verbal tics and has done so since childhood. He has never taken any medication for his symptoms and has always attended normal classes. We also tested four control participants – three men and one woman between 28 and 45 years of age. All subjects, including BF, gave their informed consent before participating.

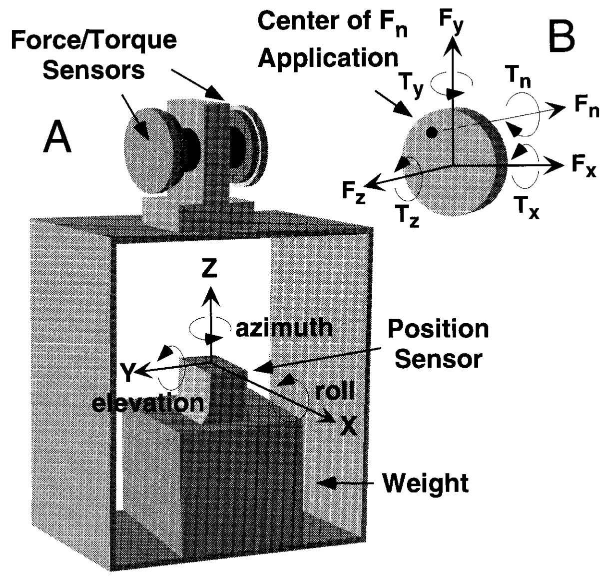

Fig. 1 The test object **(A)** consisted of a rectangular plastic frame. The handle on top of the frame was fitted with two force-torque sensors. Circular contact disks were mounted on top of each sensor. The sensors measured three forces and three torques applied at each of the disks **(B)**. A box fixed to the base of the frame added weight. Object position and orientation were measured by a six-axis position-angle sensor and described in Cartesian coordinates and Euler angles respectively **(A)**

Apparatus

The test object consisted of a plastic frame on top of which was a handle (see Fig. 1A). Two six-axis force-torque sensors (Nano F/T transducers, ATI Industrial Automation, Garner, NC) were attached on either side of the handle. Plastic contact disks (diameter 3 cm) were mounted on each of the sensors and these were covered in medium grain sandpaper (no. 220). The participant was required to grasp the test object using a precision grip with the tips of the thumb and index finger on the two opposing contact surfaces (5 cm apart). Each sensor measured the forces and torques applied by the digit in three dimensions (see Fig. 1B; see Kinoshita et al. 1997 for information on sensor resolution).

A box was fixed to the base of the frame to give added weight. Mounted on top of the box was an electromagnetic position-angle sensor (Flock of Birds, Ascension Technology, VT) which recorded the position and orientation of the object in three dimensions. The position of the object was defined in a Cartesian coordinate frame (resolution±0.15 mm). The angular orientation of the object was recorded in Euler angles: azimuth, elevation, and roll (resolution±0.05°). These angles were defined with respect to a moving coordinate frame starting with the coordinate frame used for position and rotated successively about the *z* (azimuth), *y* (elevation), and *x* (roll)-axes. The total weight of the test object was 240 g (or about 2.4 N). A Macintosh 7100 PowerPC computer with a 16-bit analog-to-digital board (Model MIO-16X-h-18, National Instruments, TX) was used for data collection.

Procedure

BF completed three different experiments (i.e., sets of trials) all within a single session lasting about 11/2 h. In all of the experiments, BF grasped the test object with a precision grip (described above).

Experiment 1

The aim of the first experiment was to examine BF's force coordination during cyclic movements and when simply holding the object in a stationary position (static holding). We recorded 22 trials of static holding, 8 trials of slow cyclic up and down movements (at about 2 Hz), 4 trials of fast cyclic up and down movements (at about 4 Hz), 3 trials of slow horizontal cyclic movements (along the *x*-axis in Fig. 1A), and a couple of trials of cyclic object rotation where the elevation angle was varied. The length of each trial was 4 s. The amplitude of the cyclic movements was about 20 cm. There were no physical targets. However, at the start of the experiment, the experimenter demonstrated the task.

Experiment 2

The key experiment was the second in which we asked BF to make vertical movements while holding the test object. On each trial, BF was verbally instructed to "get ready" to make either an "upward" or "downward" movement and then to move when hearing the GO signal. The GO signal was a snapping of the experimenter's fingers and was given after a variable delay from the "get ready" cue. Thus, BF was cued in advance whether to make an up or down movement and could not predict when the GO signal would be given. The delay period between the cue and the GO signal ranged from 2 to 10 s. During the delay period, BF frequently made tics which were almost invariably in the direction of the cued movement (i.e., he made an upward tic if he was instructed to make an upward movement).

We recorded a number of trials (6 s in duration) both during the delay period and during the movements elicited by the GO signal. In all we recorded 12 upward movements, 7 downward movements, and 34 up or down movement tics observed during the delay periods. During the delay periods, we also recorded 18 "grip force" tics – characterized by sharp increases in grip force without appreciable object motion – and one "elevation" tic in which the object was rotated. The voluntary upward and downward movements ranged between 20 and 25 cm in amplitude and most were performed quite rapidly. The motion was demonstrated by the experimenter at the start of the experiment and we did not use physical targets to guide the movement. As will be shown below, these vertical movements were often associated with significant changes in the object's elevation angle which altered the tangential torques generated at the digit contact surfaces.

Experiment 3

In the third experiment, we asked BF to grasp the object (with a precision grip) and generate isometric forces on the object which was secured to a tabletop. The aim was to assess whether there was a relation between tic direction (measured by a force change) and the direction of the background force. We recorded ten trials during which BF exerted a constant downward force (about –5 N) and nine trials in which he generated a steady upward force (about 5 N) on the object. We also recorded six trials in which BF produced ramp changes in vertical force (e.g., from an upward force to a downward force) and two trials in which he generated cyclic isometric movements ranging from –5 to 5 N. In all we recorded 24 isometric movement tics while BF was generating a steady upward or downward isometric force.

Static holding trials with control subjects

Each of the four control subjects completed four trials in which they were asked to hold the object in a stationary position. The aim was to obtain baseline measures of normal force for comparison with BF.

Slip tests

To determine the normal force safety margin (or excess grip force), it is necessary to estimate the minimum normal force (or slip force) required to prevent slip. The slip force depends on the tangential load and the coefficient of friction between the digits and the contact surfaces. To obtain estimates of the coefficient of friction, we asked each participant (including BF) to grip the test object and then slide either the index finger or thumb across the contact surface (see Kinoshita et al. 1997). The ratio of tangential force to normal force at slip onset is an estimate of the coefficient of static friction. The slip force is the load divided by the estimated coefficient of friction.

Analysis

The position and orientation of the object were sampled at 100 Hz and the forces and torques were sampled at 200 Hz. The measured position and force data were used directly (without filtering) for plotting and analysis. However, a second-order low-pass Butterworth filter with a cutoff frequency of 10 Hz was used to filter the position data prior to differentiation to obtain velocity and acceleration records.

We computed the tangential force (F_t) acting at each contact surface given by the vector sum of F_x and F_y. The grip force or normal force (F_n) was defined as $-F_z$. We also computed the tangential torque (T_n) acting about the vector normal to the contact surface and intersecting the center of normal force pressure (Fig. 1B; see Kinoshita et al. 1997 for details). In addition, we computed the total tangential load, *L*, which takes into account both the force (F_t) and torque (T_n) tangential to the contact surface (see Kinoshita et al. 1997). For a given coefficient of friction, the tangential load determines the normal force required to prevent slip.

For the control subjects, we computed the mean normal force during each of four 2-s trials and then took the average of these mean values. For BF, we computed the mean normal force during 1-s periods of static holding in which tics were absent and took the average of the means (n=40). We also measured the mean normal force over 1-s intervals immediately prior to and immediately following tics and voluntary movements. In addition to mean normal force, we computed the relative normal force safety margin, which is the excess normal force divided by the employed normal force: $(F_n - F_s)/F_n$.

Results

Voluntary movements

We found that all of BF's voluntary movements (including his isometric movements) exhibited a normal pattern of coordination. In particular, BF's movements were smooth and grip force and load were tightly coupled. Figure 2 shows kinematic and kinetic records from three single trials: a discrete upward movement, a discrete downward movement, and a cyclic up and down movement. At the start of the upward movement, the tangential force (F_t) starts to rise towards a peak which coincides with the peak upward acceleration (z'') and the load (L) also starts to rise. The grip or normal force (F_n) begins to increase at about the same time as the tangential force. In all of BF's upward movements, normal force began to rise either at or slightly before the load and thus anticipated the load. The normal force levels off around the peak tangential force but then increases again and remains elevated at the end of the movement. This second

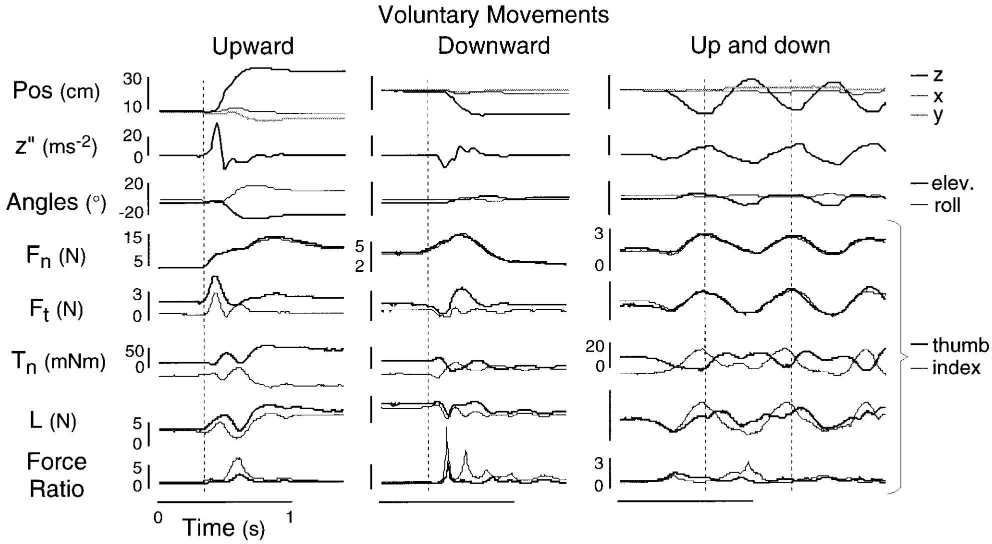

Fig. 2 Kinematic and kinetic records obtained during voluntary movements. *Each panel* shows records from a single trial. The calibration values shown *in the left panel* apply to all panels unless otherwise indicated. In all three movements shown, normal force (F_n) is adjusted in anticipation of movement-induced load (L), which reflects both tangential forces (F_t) and tangential torques (T_n) applied by the digits. *The vertical dashed lines* indicate movement onset *in the left and middle panels* and times of peak normal force *in the right panel*

increase in normal force prevents slip that would otherwise result from the increase in *magnitude* of the torques (T_n) observed at the end of the movement. The increase in absolute torque at both digits is due to tilting of the object as reflected by the negative elevation angle. In this particular trial, there was a large change in the roll angle. However, in general the roll angle did not deviate very much during the movement (see, for example, the cyclic movement in Fig. 2) When one takes both the tangential forces and the tangential torques into account – as reflected by the load – it is clear that normal force is adjusted appropriately and in an anticipatory fashion.

Precise anticipatory normal force adjustments are also evident in the downward and cyclic movement records shown in Fig. 1. In the downward movement, the peak tangential force occurs towards the end of the movement (as the object is decelerated against gravity). Once again, the normal force starts to increase at the start of the movement and the peak normal force coincides with the peak tangential force. The magnitudes of the torques decrease in the downward movement (reflecting a small change in elevation angle) and as a consequence both the load and the normal force are smaller at the end of the movement than at the start. In the cyclic up and down movement, normal force is adjusted in phase with, and thus anticipates, fluctuations in the tangential force (or load). Although not shown in the figure, there was also a close coupling between grip force and load during BF's isometric cyclic movements.

As noted above, BF often tilted the object when moving up. This indicates that when flexing the elbow BF did not fully compensate with wrist rotation. As a consequence of tilting, substantial torques were generated at the contact surfaces at the end of movement. Had we only considered the tangential forces, we would have mistakenly concluded that BF exhibited excessively high normal forces at the end of upward movements (and at the start of downward movements). Thus, measurement of torques was critical in this task and is an important consideration when assessing grip control under conditions in which movement kinematics are not tightly controlled.

To summarize, in all of BF's voluntary movements, we saw a close coupling between normal force and load. Normal force was adjusted in phase with changes in load brought about by movement. BF generated accurate anticipatory grip adjustments in both discrete and cyclic movements (and in cyclic isometric movements). The overall pattern of his results is entirely consistent with previous reports of the coupling between grip force and load during arm movements (Flanagan and Wing 1993, 1995).

Movement tics

Having established that BF's voluntary movements feature anticipatory and appropriate normal force adjustments, we now turn to his movement tics that were elicited in the cueing experiment.

The first main finding was that we were able to elicit tics in a particular direction by cueing BF to move in that direction on a GO signal delivered after a variable delay period. The left-hand side of Table 1 shows the number of upward and downward tics produced when BF was cued to move up or down. Overall we observed 34 movement tics of which 31 (91%) were in the cued direction. The remaining three movement tics were in the opposite direction. A chi-square test supported the observation that cue direction and tic direction are dependent (χ^2=23.9; P<0.001). We also observed 18 "grip force" tics during which there was a phasic increase in normal force but no appreciable movement. Note that BF never generated a voluntary movement in the incorrect direction or failed to respond to the GO signal. That is, when instructed to move up, he always moved up after the GO signal and when instructed to move down, he always moved down after the GO signal.

Table 1 Frequencies of upward and downward tics as a function of cued movement direction (left) in the cueing task and the direction of the background force applied during the isometric task

Tic frequencies							
Vertical movements				Constant isometric forces			
		Tic direction				Tic direction	
		Up	Down			Up	Down
Cued direction	Up	16	3	Background force direction	Up	11	4
	Down	0	15		Down	4	5

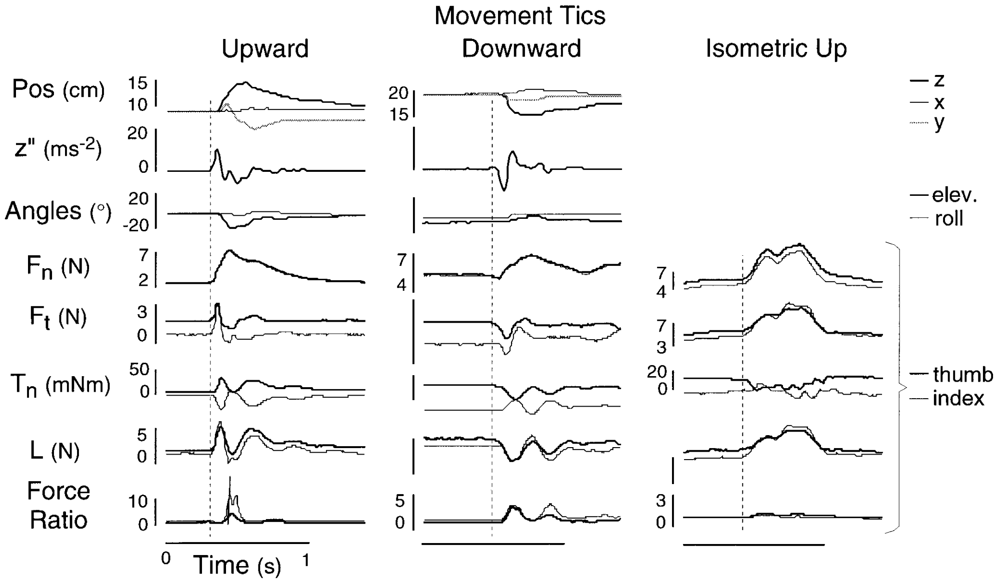

Fig. 3 Kinematic and kinetic records obtained during tics. *Each panel* shows records from a single trial. The calibration values shown *in the left panel* apply to all panels unless otherwise indicated. *The right panel* shows a tic generated under isometric conditions and thus kinematic records are not shown. In all three tics, normal force (F_n) is adjusted in anticipation of movement-induced load (L), which reflects both tangential forces (F_t) and tangential torques (T_n) applied by the digits. *The vertical dashed lines* indicate movement onset

We also analysed movement tics in the isometric task during which BF generated constant tangential forces in either the up or down direction. The frequencies of observed upward and downward tics as a function of the background force are shown on the right-hand side of Table 1. (Note that an upward isometric tic, for example, is associated with a brief and rapid increase in tangential force.) Although BF produced many more upward tics than downward tics when pulling up on the test object, he produced about the same number of upward and downward tics when pushing down. Overall, of the 24 movement tics we recorded, 16 (67%) were in the direction of the background isometric tangential force. A chi-square test failed to show a reliable dependence of tic direction on background force direction ($\chi^2_{(1)}$=2.0; P=0.157). We also observed six grip force tics in the isometric task.

The second main result is that BF's movement tics are associated with anticipatory normal force adjustments and close coupling between normal force and load. Figure 3 shows records from three trials in which tics were observed. The upward and downward tics shown in the figure occurred during the delay period between the cue to move (up and down respectively) and the GO signal. The isometric tic occurred while BF was pulling up on the (fixed) object with a constant force. All of the tics are characterized by a rapid and relatively small movement followed by a corrective motion which returns the object (or background force) to the position (or force) observed prior to the tic.

Consider the upward tic shown in Fig. 3. The amplitude of the tic was relatively small in amplitude (7 cm) and consisted of an upward motion followed by a return movement. (This was the general pattern in all tic trials. In this particular trial, there was some sideways motion, most of which occurred after the initial upwards acceleration.) Because the tic movement was rapid, the resulting peak load was comparable in amplitude to peaks observed during voluntary upward movements (see Fig. 2). In this trial, an initial load peak – near the start of the movement – was followed by a second peak. The load then decreased at the end of the movement. The key observation is that grip force also increased at the start of the movement, remained elevated at the time of the second load peak, and then gradually decreased at the end of the movement. Thus, we can see that grip force was adjusted in phase with the load and clearly anticipated the changes in load. Note that when the load decreases and then increases briefly during the movement, normal force remains relatively high. This tendency for normal force not to track large and brief drops in load that occur during movement has been documented previously (Flanagan and Wing 1993, 1995, 1997).

Precise anticipatory adjustments in normal force are also seen in the downward tic shown in Fig. 3. In this trial, the load (and the tangential force) decreases at the start of the movement and then peaks towards the end. Consistent with this pattern of loading, the normal force does not begin to increase at the very start of the trial (indeed there is a slight decrease). However, the normal starts to increase soon after movement onset and reaches a peak that coincides with the peak load. Thus, once again, normal force was modulated in phase with fluctuations in the load. A close coupling between normal force and load (and tangential force) is also observed in the upward isometric tic shown in Fig. 3. Normal force begins to increase at the same time as the load and changes in parallel with the load throughout the movement.

Force ratios and safety margins

Johansson and Westling (1984) have shown that the ratio of normal force to load – or force ratio – is a precisely controlled variable. Provided that the friction between the digits and the contact surfaces remains constant, subjects scale normal force for changes in load such that the force ratio is fairly stable (except when the load approaches zero). These investigators have also shown that subjects employ a relatively small normal force safety margin. If tics are involuntary and cannot be predicted by the motor system, we might expect individuals with TS to employ elevated normal forces to guard against slips that would otherwise be caused by sudden movement-induced loading. To evaluate this possibility, we compared the relative safety margins (excess normal force over normal force) employed by BF with the margins used by the four control subjects. The relative safety margins estimated for the four control subjects were 0.50, 0.43, 0.39, and 0.34 (averaging across trials and digits). The relative safety margin estimated for BF was 0.36 and is well within the range of values obtained for the controls. BF's relative safety margin is also within the range of values reported in the literature for medium grain sandpaper (e.g., Kinoshita et al. 1996). Thus, examination of relative safety margins does not support the notion that BF employed excessive normal forces when holding the object in a stationary position.

Normal subjects do not elevate normal force in the period before a movement (Flanagan and Wing 1993). We wondered whether BF might elevate his normal force before movement tics. Such behaviour would suggest that he is uncertain of his ability to appropriately modulate normal force during the tic. To test this idea, we computed mean force ratios (F_n/L) over 1-s intervals immediately prior to tics, immediately following tics, and in trials in which there were no tics. We also computed mean force ratios over 1-s intervals just prior to and immediately following voluntary movements. The averages of these mean ratios for each phase (i.e., interval type) and digit are shown in Table 2. Post hoc pairwise comparisons (Tukey's B-test) failed to reveal reliable differences, between phases, in the force ratios of either digit (P>0.05 in all cases).

Table 2 Force ratios for the thumb and index finger measured during periods of static holding in trials without tics, immediately prior to tics, immediately following tics, immediately prior to voluntary movements, and immediately following voluntary movements

	n	Force ratios			
		Thumb		Index	
		Mean	SD	Mean	SD
No tics	35	1.04	0.22	1.37	0.37
Pre-tic	21	1.07	0.24	1.40	0.43
Post-tic	19	1.07	0.23	1.60	0.38
Pre-movement	13	1.08	0.22	1.50	0.64
Post-movement	13	1.02	0.25	1.54	0.47

Discussion

This study has yielded two novel findings. First, we found that so-called involuntary tics are accompanied with appropriate and precise anticipatory normal force adjustments. To our knowledge, this is the first clear demonstration that movement tics in TS involve anticipatory or predictive control mechanisms generally associated with intentional, goal-directed movements. Second, we have shown that tics in a particular movement direction can be elicited by cueing the participant to move in that direction after receiving a GO signal to be given after a delay period.

If tics are involuntary and cannot be predicted by the motor system, we might expect individuals with TS to employ elevated normal forces to guard against slips that could otherwise be induced by sudden movements. Excessive normal force would be reflected in elevated normal force safety margins. However, we found that the relative safety margins used by BF were within the range of margins used by the control subjects we tested. This finding is consistent with the general hypothesis that tics in TS can be anticipated at the level of postural (i.e., grip) adjustments. Once again, if the motor system is able to predict movement tics then there would be no need to employ an elevated normal force safety margin.

We found that the direction of a tic is strongly determined by the cued movement direction. In contrast, we found that tic direction does not appear to be influenced by the direction of background force during the application of constant isometric forces. These findings suggest that the tics were related to planned or intended movements rather than the current state (output) of the motor system.

It is interesting to speculate on why BF generated tics in the cued directions during the delay period. One possibility is that cueing a particular direction may cause a motor plan or program to be prepared. Once the program is in place, it may be difficult for BF to suppress execution of the program when instructed to wait for a GO signal. Another possible explanation is that BF has difficulty suppressing movements or gestures that are inappropriate. By instructing BF to wait until the GO signal, we made movements (or tics) during the delay period inappropriate. Some support for this view comes from observations on BF made during a separate set of experiments on phonic tics. In these experiments, we were assisted by a female undergraduate and we noted that BF was much more likely to utter swear words derogatory to women when she was in the laboratory. The "inappropriateness" explanation, however, must be qualified. After all, recall that BF never produced a voluntary movement in the incorrect direction; i.e., opposite the cued direction. In future work, it would be interesting to manipulate the "cost" of moving before the GO signal. If the "inappropriateness" notion is correct, then more tics should be observed as the cost goes up. However, this function may well be an inverted "U" such that when the cost of ticing becomes serious or extreme the tics may stop. The physician with Tourette's syndrome described by Oliver Sacks (1995) was able to perform surgery and fly an airplane, which suggests that he was able to suppress what would be potentially lethal tics in these circumstances.

We recognize that the tics observed in the present cueing task may be different than tics generated under other conditions. For example, cueing may lead to the preparation of organized motor programs which result in tic behaviours that are similar to voluntary movements. When cueing is absent, prepared motor programs may not be available when tics are generated. We cannot rule out this possibility based on the present results. However, it is worth noting that in pilot work without cueing, we recorded a couple of movement tics that happened to be directed vertically (and thus orthogonal to the grip axis). In these trials, grip force was adjusted in anticipation of movement-induced changes in the load force.

In summary, we stress the two main findings of this research: (1) movement tics feature appropriate and precise anticipatory normal force adjustments characteristic of voluntary movements and (2) tics in a particular direction can be elicited by cueing the participant to move in that direction after a delay period and on a GO signal. The results support the hypothesis that tics in TS are purposefully executed and well-coordinated movements. In other words, the findings justify the "tic" in anticipation!

Acknowledgements This work was supported by the Natural Sciences and Engineering Council of Canada.

References

Cole KJ, Abbs JH (1988) Grip force adjustments evoked by load force perturbations of a grasped object. J Neurophysiol 60: 1513–1522

Flanagan JR, Tresilian JR (1994) Grip-load force coupling: a general control strategy for transporting objects. J Exp Psych: Hum Percept Perform 20:944–957

Flanagan JR, Wing AM (1993) Modulation of grip force with load force during point-to-point movements. Exp Brain Res 95: 131–143

Flanagan JR, Wing AM (1995) The stability of precision grip force during cyclic arm movements with a hand-held load. Exp Brain Res 105:455–464

Flanagan JR, Wing AM (1997) The role of internal models in motor planning and control: evidence from grip force adjustments during movements of hand-held loads. J Neurosci 17:1519–1528

Flanagan JR, Tresilian JR, Wing AM (1993) Coupling of grip force and load force during arm movements with grasped objects. Neurosci Lett 152:53–56

Gilles de la Tourette G (1885) Étude sur une affection nerveuse caracterisée par de l'incoordination motrice accompagnée d'écholalie et de copralalie. Arch Neurol 9:19–42; 158–200

Glaze DG, Frost JD, Jankovic J (1983) Sleep in Gilles de la Tourette syndrome: disorder of arousal. Neurology 33:586–592

Jakobson LS, Flanagan JR, Munhall KG (1996) Anticipatory control of precision grip force in Tourette's syndrome. Soc Neurosci Abstr 22(1):427

Jankovic J (1997) Phenomenology and classification of tics. Neurol Clin 15: 267–275

Jankovic J, Fahn S (1986) The phenomenology of tics. Mov Disord 1:17–26

Jankovic J, Rohaidy H (1987) Motor, behavioral and pharmacologic findings in Tourette's syndrome. Can J Neurol Sci 14:541–546

Johansson RS (1996) Sensory control of dexterous manipulation in humans. In: Wing AM, Haggard P, Flanagan JR (eds) Hand and brain: neurophysiology and psychology of hand movement. Academic Press, San Diego, pp 381–414

Johansson RS, Cole KJ (1992) Sensory-motor coordination during grasping and manipulation actions. Curr Opin Neurobiol 2:815–823

Johansson RS, Westling G (1984) Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. Exp Brain Res 56: 550–564

Johansson RS, Riso R, Hager C, Backstrom L (1992) Somatosensory control of precision grip during unpredictable pulling loads. Exp Brain Res 89:181–191

Karp BI, Porter S, Toro C et al. (1996) Simple motor tics may be preceded by a premotor potential. J Neurol Neurosurg Psychiatry 61:103–106

Kinoshita H, Backstrom L, Flanagan JR, Johansson RS (1997) Planar torque effects on grip force during precision grip. J Neurophysiol 78:1619–1630

Lang A (1991) Patient perception of tics and other movement disorders. Neurology 41:223–228

Lang AE, Consky E, Sandor P (1993) "Signing tics" – insights into the pathophysiology of symptoms in Tourette's syndrome. Ann Neurol 33:212–215

Lees AJ (1985) Tics and related disorders. Churchill Livingston, New York

Obeso JA, Rothwell JC, Marsden CD (1982) The neurophysiology of Tourette's syndrome. Adv Neurol 35:105–114

Sacks OW (1995) An anthropologist on Mars: seven paradoxical tales. Knopf, New York

Shapiro AK, Shapiro ES, Young JG, Feinberg TE (1988) Gilles de la Tourette syndrome. Raven Press, New York

Westling G, Johansson RS (1987) Factors influencing the force control during precision grip. Exp Brain Res 53:277–284

Wing AM (1996) Anticipatory control of grip force in rapid arm movements. In: Wing AM, Haggard P, Flanagan JR (eds) Hand and brain: neurophysiology and psychology of hand movement. Academic Press, San Diego, pp 301–324