Deliberate Control of Continuous Motor Performance

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ABSTRACT. The authors examined the means by which people vary movement parameters to satisfy more than 1 constraint at a time in a repetitive motor task. The authors expected that when participants \( N = 12 \) were simultaneously confronted with spatial and temporal constraints in an ellipse-drawing task, they would either exploit the intrinsic amplitude–frequency relationships or activate less natural control regimes to prioritize their movement goals. By focusing on local amplitude and frequency errors and parameter changes from 1 movement to the next, the authors distinguished parameter changes that reflected exploitation of biomechanics from those that required deliberate control. The findings demonstrated that at low movement speeds, participants can pursue multiple movement goals simultaneously; at higher speeds, their capacity to satisfy multiple task goals is reduced. The authors used a new method of inferring deliberate control from movement kinematics in the present study.

Key words: circle drawing, constraint satisfaction, deliberate control, kinematics, motion planning

Individuals tend to perform large-amplitude arm movements at low frequencies by means of shoulder and elbow rotations, whereas they tend to perform small-amplitude arm movements at higher frequencies by means of wrist and finger rotations (Rosenbaum, Slotta, Vaughan, & Plamondon, 1991; Vaughan, Matson, & Rosenbaum, 1998; Vaughan, Rosenbaum, Diedrich, & Moore, 1996). Asking participants to depart from those movement patterns (e.g., to produce fast shoulder movements or slow wrist rotations) requires them to refrain from relying on intrinsic amplitude–frequency relationships and instead to activate less natural, possibly more attention-demanding, control regimes (cf. Swinnen & Wenderoth, 2004; Zelaznik, Spencer, & Ivry, 2002). How do participants achieve such control?

To address that question, we studied the continuous drawing of ellipses (see also Meulenbroek, Bouwhuisen, Thomassen, & Rosenbaum, 1999; Meulenbroek, Thomassen, Van Lieshout, & Swinnen, 1998; Thomassen & Meulenbroek, 1998). Participants were supposed to match the amplitudes and frequencies of their movements to target values that varied from trial to trial. Our predictions about the way the ellipses would be controlled were based on known biomechanical interdependencies between movement amplitude and frequency (Kay, Kelso, Saltzman, & Schöner, 1987; Rosenbaum et al., 1991). The reader can understand the predictions by consulting Figure 1.

A hypothetical goal amplitude–frequency combination is shown in the center of Figure 1. Around the centrally located goal-parameter combination are eight categories of possible performance errors. Single parameter errors are shown on the \( x \) and \( y \) axes, whereas double parameter errors (i.e., errors in both amplitude and frequency) are depicted in the four quadrants. Figure 1 also shows a hypothetical series of attempts to reduce the errors from one movement to the next in response to performance error. In the depicted case, the initial error is an amplitude that is too short \( (A^-) \) and a frequency that is too high \( (F^+) \). The error-reduction process is represented by a sequence of four arrows.

Let movement \( i \) be a single loop of particular amplitude and frequency. Various outcomes are possible for movement \( i + 1 \). One possibility is that both the amplitude and frequency of movement \( i + 1 \) are identical to those of movement \( i \). By contrast, one or both of the parameters of movement \( i + 1 \) may differ from those of movement \( i \), in which case one of the three following outcomes is possible:

1. Either the amplitude or the frequency of movement \( i + 1 \) differs from that of movement \( i \). In both cases, we speak of a single parameter change.

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2. The amplitude of movement \( i + 1 \) increases and the frequency of movement \( i + 1 \) decreases, or the amplitude of movement \( i + 1 \) decreases and the frequency of movement \( i + 1 \) increases. In both cases, two parameters change, but the participant may have intentionally changed only one parameter and the other parameter may have changed passively on the basis of the natural relationship between amplitude and frequency. We call such changes quasi-double parameter changes.

3. Both the amplitude and the frequency of movement \( i + 1 \) increase or decrease. Here we speak of intentionally driven double parameter changes because the combined changes defy the natural, biomechanical relationship between the two parameters (i.e., the inverse relation between frequency and amplitude).

A final important aspect of the transition is whether the parameter changes from movement \( i \) to movement \( i + 1 \) do or do not reduce the error relative to the instructed amplitude and frequency. Each of the aforementioned changes can be classified as being successful (smaller error) or unsuccessful (larger error or no reduction in error).

By scrutinizing the amplitude and frequency errors and subsequently determining the incidence and size of single, double, and quasi-double parameter-error changes as well as the success of such changes, we sought to identify those movement-parameter adjustments that were primarily a result of deliberate attempts by the participant to meet the task goal. Because the double parameter changes defied the biomechanically given inverse relation between amplitude and frequency, we assumed that they were deliberate. Therefore, because deliberate control takes time and is more likely to be manifested when there is time for it to operate, we predicted that there would be an appreciable number of such changes and that there would be more of them when the required tempo of movement was slow than when it was fast. In addition, we expected that in low-speed conditions, double parameter changes would occur most often when local errors consisted of combined amplitude and frequency overshoots or undershoots. The reason for that prediction is that double parameter changes would provide the most efficient means of error reduction, and the deliberate control required to achieve such efficient error reduction would be easier at low than at high speeds.

### Method

#### Participants

Twelve right-handed adults (6 women and 6 men) participated. Their mean age was 24 years and 9 months (range = 14 years, 6 months). All participants had normal hearing and normal or corrected-to-normal vision. None had motor problems. All participants gave their informed consent and received course credits or payment. Experimental procedures followed the American Psychological Association guidelines for the ethical treatment of human participants.

#### Task and Procedure

Before the experiment began, the participant was given written instructions and was asked to write his or her name on a normal sheet of white paper. We used the orientation at which the participant spontaneously positioned the sheet on the writing surface to align a rectangular projection area (25 cm × 20 cm) that was displayed on the writing surface by means of a liquid-crystal display (LCD) video and a surface mirror, both positioned under the writing table. A translucent surface (30 cm × 25 cm) built into the writing table allowed for rear (or bottom) projection of the display.

The bottom of the projection area (closest to the participant) served as the orientation of the baseline of the writing during the entire 90-min experiment. Before the experiment began, we calibrated the translations of the tip of the pen onto the x and y dimensions of the participant’s preferred graphic workspace. For that purpose, we used a three-dimensional (3D) rigid coordinate frame. Following the reference recordings, we asked the participant to adopt a comfortable writing posture.

The experiment consisted of 100 trials and was self-paced. Participants wrote on a 6-cm-high paper strip that they were
As the cursor moved up, the acoustic signal’s intensity mapped onto the vertical displacements of the moving cursor. The intensity change of the acoustic pacing signal was sor, an acoustic signal that changed sinusoidally in intensity we also decided to present, in synchrony with the moving cursor. Because acoustic stimuli are processed more quickly than visual ones, participants realize the required movement frequencies. Therefore, we added to lock their writing movements onto a moving cursor when the cursor moved at a frequency of 5 Hz. Therefore, we added an additional pacing signal that we thought would help participants to perform the next trial. A trial consisted of three phases. During the first phase, which lasted 5 s, the cursor moved along the ellipse and the acoustic pacing signal sounded. During the second phase, the acoustic pacing signal was turned off for a single cycle of the moving cursor. During the third and final phase, we reintroduced the acoustic pacing signal, and the cursor started to move rightward along the stimulus loop pattern. The cursor was projected so that it was clearly visible to the participant. Watching the cursor and the simultaneously written trace did not require significant eye or head movements. Participants were asked to copy the pattern by following the moving cursor and trying to reflect its position as accurately as possible. A trial ended when the cursor moved through 12 loops. We recorded movements throughout the trial. We replicated four times each of the 25 amplitude–frequency combinations, which resulted in 100 trials. We changed amplitude–frequency conditions after a block of four replications. Half the participants were given a sequence in which amplitudes and frequencies increased in successive trials. We gave the other half of the participants a sequence in which amplitudes and frequencies decreased in successive trials.

Recording System

We mounted one rigid body, consisting of three infrared-light-emitting diodes (IREDS) fixated at a 1- × 1- × 1-cm inter-IRED distance on a flat aluminum plate on the top of the barrel of a normal ballpoint pen (Bouwhuisen, Meulenbroek, & Thomassen, 2002). We recorded translations and rotations of the rigid body at a rate of 100 Hz and with a spatial accuracy higher than 0.2 mm in the x and y directions by means of a 3D motion tracking system (Optotrak 3020, Northern Digital Inc., Waterloo, Canada). The position and orientation of the rigid body were transformed to the position of the pen tip.

Data Analysis

We filtered the digitized pen-tip displacement signals in the x and y directions with a second-order, dual-pass Butterworth filter. The high-pass frequency was 0.5 Hz for all signals, which eliminated the movement components related to the low-speed rightward progression component of the movements. We set the low-pass cut-off frequency of the filter to twice the pacing frequency of the condition in which the signal was recorded. That frequency ensured that we could reliably apply an automatic peak–valley detection algorithm to each position–time signal. On the basis of that algorithm, we extracted successive cycles by means of a peak–peak detection algorithm (Hollerbach, 1981; Meulenbroek et al., 1998). Describing successive cycles by their peak amplitude and frequency allowed us to quantify the biomechanically and non-
biomechanically induced relationships between movement amplitude and frequency.

For each obtained movement cycle, we calculated the realized amplitude for the detrended x and y position–time signals separately. Then, we averaged the amplitude in the horizontal and the vertical dimensions to obtain a local cycle amplitude, \( A \), expressed in millimeters. We applied a similar procedure to arrive at a local cycle frequency, \( F \), expressed in hertz. Next, we used parameters \( A \) and \( F \) to calculate the local spatial error, \( A_{err} \), expressed as a percentage of the instructed amplitude, where positive values reflected amplitude overshoots and negative amplitudes reflected amplitude undershoots. Similarly, we expressed the local frequency error, \( F_{err} \), as a percentage of the instructed frequency, where positive values reflected higher than instructed frequencies and negative values represented lower than instructed frequencies. Thus, \( A_{err} \) and \( F_{err} \) reflected the signed relative amplitude and frequency errors, respectively, given the instructed amplitude and frequency values conveyed by the moving cursor.

The next step concerned quantifying the error changes from one movement to the next. Except from the first movement cycle in each trial, we obtained for each cycle the two parameters \( \Delta A_{err} \) and \( \Delta F_{err} \), where \( \Delta A_{err} \) equaled \( A_{err} \) of cycle \( i \) minus \( A_{err} \) of cycle \( i - 1 \), and \( \Delta F_{err} \) equaled \( F_{err} \) of cycle \( i \) minus \( F_{err} \) of cycle \( i - 1 \).

We used a minimum value, \( d \), set at 1% of the local instructed parameter value, to identify a change in parameter value. Any absolute value greater than or equal to that value qualified as a parameter-value change.2 To test our predictions, we first categorized the \( A_{err} \) and \( F_{err} \) data into the eight classes indicated on the axes and in the quadrant centers of Figure 1. The eight categories represented all possible combinations of overshoots and undershoots in the amplitude and frequency domains. Subsequently, we classified each \( \Delta A_{err} \) and \( \Delta F_{err} \) combination, representing the error change realized from one movement to the next as a single parameter change, a quasi-double parameter change, or a double parameter change.

We used sign tests to evaluate the statistical significance of observed differences between the incidences of movement error categories. We also used sign tests to evaluate the incidence of the categories of parameter changes. Those nonparametric tests were more conservative than chi-square tests in this context. We used paired-samples \( t \) tests to evaluate the statistical significance of the size of the observed movement errors and parameter changes. We applied Bonferroni corrections whenever we conducted multiple tests.

**Results**

The results are presented as follows: First, we report the incidence and size of the observed amplitude and frequency errors. Second, we present the incidence and size of single, double, and quasi-double parameter changes from one movement to the next, collapsed over the five speed conditions of the experiment. Third, we evaluate the study’s main prediction that double parameter changes will occur most frequently when the required tempo of movement is slow.

**Amplitude and Frequency Errors**

We evaluated 51,555 movement cycles with respect to (a) the realized amplitude and frequency relative to the goal amplitude and frequency and (b) the realized parameter change from one movement to the next.

The cells in Table 1 are arranged in a 3 × 3 matrix and show the incidence of the eight categories of possible perfor-

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**TABLE 1. Incidence of Amplitude and Frequency Errors Expressed as Percentage of the Local Goal Parameter**

<table>
<thead>
<tr>
<th>Frequency error</th>
<th>Too small</th>
<th>No error</th>
<th>Too large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too high</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local goal parameter</td>
<td>(( F_{err} = +7% ; A_{err} = -22% ))</td>
<td>(( F_{err} = +7% ))</td>
<td>(( F_{err} = +7% ; A_{err} = +19% ))</td>
</tr>
<tr>
<td>No error</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local goal parameter</td>
<td>(( A_{err} = -21% ))</td>
<td>(( A_{err} = +20% ))</td>
<td></td>
</tr>
<tr>
<td>Too low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local goal parameter</td>
<td>(( F_{err} = -8% ; A_{err} = -21% ))</td>
<td>(( F_{err} = -8% ))</td>
<td>(( F_{err} = -8% ; A_{err} = +19% ))</td>
</tr>
</tbody>
</table>

**Note.** Positive values represent parameter overshoots; negative values reflect parameter undershoots. The central cell represents the absence of any error. Local spatial error, \( A_{err} \), and local frequency error, \( F_{err} \), are both expressed as a percentage. Mean percentage parameter change size—local frequency error change and local spatial error change (\( \Delta F_{err} \) and \( \Delta A_{err} \), respectively)—are specified in parentheses.
Performance errors collapsed over the five instructed amplitudes and five instructed frequency conditions. The mean sizes of the errors are specified in parentheses. The number of movements for which both the amplitude and frequency were on target is shown in the center of Table 1. Note that this number is low, as expected, because of the stringent criterion we used to identify errors and error changes (i.e., 1% of each of the two goal parameters; see Method section and Note 2).

**Incidence**

All participants produced more amplitude undershoots than overshoots (sign test, \(N = 12, p < .001\)). However, the incidence of positive (42.26%) and negative (43.56%) frequency errors proved statistically indistinguishable (sign test, \(N = 12, ns\)).

**Size**

The size of the amplitude errors (\(M = 20.61\%, SD = 4.73\%) was, on average, almost 3 times the size of the frequency errors (\(M = 7.61\%, SD = 1.78\%), t(11) = 10.01, p < .001\), suggesting that participants were more tolerant of amplitude errors than frequency errors. However, the size of the amplitude overshoots (\(M = 19.21\%, SD = 4.12\%) was statistically indistinguishable from the size of the amplitude undershoots (\(M = 22.01\%, SD = 7.12\%), t(11) = 1.44, ns\). Similarly, the positive and negative frequency errors were statistically indistinguishable (\(M = 7.34\%, SD = 2.17\%, and M = 7.88\%, SD = 2.14\%\), respectively), \(t(11) = 0.77, ns\).

Figure 3 shows the time course of the size of the first seven unsigned (top panel) and first seven signed (bottom panel) parameter errors. To avoid clutter, we included in the figure data only from error categories with an incidence higher than 5%. The figure shows that the mean size of the amplitude and frequency errors decreased sharply over the first movement cycle and then continued to decrease gradually over subsequent movement cycles. Amplitude errors were, on average, almost 3 times larger than frequency errors. Those observations were comparable within each of the five shown error categories (bottom panel). A control analysis of between-trial error reduction revealed that offline parameter changes were restricted to movement amplitude; and, in those cases, the error reductions were considerably smaller than the within-trial performance improvements.

Figure 4 shows trial-to-trial changes in performance that were realized offline (i.e., between trials). The amplitude errors for low (1 and 2 Hz) and medium (3 Hz) movement speeds were larger in the first trial (\(j\)) than in subsequent trials within the same block (\(j + 1, j + 2, \text{and } j + 3\)). At high movement speeds (4 and 5 Hz), the amplitude error did not decrease between trials. At low movement speeds, the amplitude error was gradually reduced between trials \(j, j + 1, \text{and } j + 2\); and at medium movement speeds, between trials \(j \text{ and } j + 1\). In contrast, the frequency error was reduced between trials \(j \text{ and } j + 1\) only if the participants moved slowly (low movement speed).

**Parameter Changes From One Movement to the Next**

Table 2 shows the three types of parameter changes (single, double, and quasi-double) as a function of the three categories of error change (increase, decrease, and increase and decrease), expressed as a percentage of the local goal parameter. The mean sizes of the parameter changes (\(\Delta F_{\text{err}}\) and \(\Delta A_{\text{err}}\) are specified in parentheses. Details concerning the table follow.
Incidence

In general, participants obeyed the task instructions by trying to satisfy both the requested amplitude and frequency constraints. From one movement to the next, they succeeded in changing the local movement parameters toward the goal movement parameters. Thus, all participants produced more movements that reduced either one or both parameter errors than movements that caused both local movement parameters to drift away from the goal parameter combination (sign test, $N = 12, p < .001$). Although the size difference was small, the outcome fit with the observation that participants had a much larger tolerance for amplitude errors than for frequency errors. Consequently, the parameter range left for improvement was larger for amplitude than for frequency. Furthermore, the size of the amplitude changes that reduced the error ($M = 8.35\%, SD = 0.76\%$) was larger, on average, than the amplitude changes that increased the error ($M = 7.59\%, SD = 0.64\%$), $t(11) = 7.42, p < .001$. Also, the size of error-reducing frequency changes ($M = 4.44\%, SD = 0.38\%$) was larger, on average, than the size of the error-increasing frequency changes ($M = 3.93\%, SD = 0.43\%$), $t(11) = 5.18, p < .001$.

Single, Double, and Quasi-Double Parameter Changes

Incidence

As expected, an appreciable number of moment-to-moment changes in performance were double parameter changes (30.08%; see Table 2). Whereas single and double parameter changes were statistically indistinguishable (sign test, $N = 12, ns$), all 12 participants produced more quasi-double (41.37%) than double (30.08%) or single (26.64%) parameter changes (sign tests, $Ns = 12, ps < .001$).

Size

On average, the amplitude changes were significantly larger in the quasi-double parameter changes ($M = 9.32\%, SD = 0.83\%$) than in the double parameter changes ($M = 8.03\%, SD = 0.62\%$), $t(11) = 9.67, p < .001$, and in the single parameter change ($M = 6.95\%, SD = 0.91\%$), $t(11) = 10.30, p < .001$. Moreover, the amplitude changes were larger in the single parameter changes than in the double parameter changes, $t(11) = 2.99, p < .001$. Also, the size of the frequency change was, on average, significantly larger in the quasi-double parameter changes ($M = 6.11\%, SD = 0.49\%$) than in the double parameter changes ($M = 5.64\%, SD = 0.47\%$), $t(11) = 11.06, p < .001$, and single parameter changes ($M = 1.05\%, SD = 0.25\%$), $t(11) = 38.60, p < .001$. Finally, the mean size of the frequency change of the double parameter was significantly larger than that of the single parameter change, $t(11) = 39.81, p < .001$.

Single, Double, and Quasi-Double Parameter Changes as a Function of Movement Speed

Incidence

The incidences of single, quasi-double, and double parameter changes as a function of movement speed are shown in the top panel of Figure 5. The percentages of the quasi-double (37.83%) and double (42.56%) parameter changes at the lowest movement speed were statistically indistinguishable (sign test, $N = 12, ns$). However, for all participants, both quasi-double and double parameter changes occurred more often than single parameter changes (18.62%; sign test, $N = 12, p < .001$). As expected, in the 2-Hz mode, all 12 participants produced more quasi-double parameter changes.
(49.42%) than double (29.92%) or single (19.34%) parameter changes (sign tests, Ns = 12, ps < .001). Eleven of the 12 participants produced more double than single parameter changes (sign test, N = 12, p < .05) in the 2-Hz mode. In the 3-Hz mode, the percentages of single (26.31%) and double (28.14%) parameter changes were statistically indistinguishable (sign test, N = 12, ns), but both were lower than the quasi-double parameter changes (sign test, N = 12, p < .001) for all 12 participants. In the 4-Hz mode, for 11 of the 12 participants, the incidence of double parameter changes (25.76%) was lower than that of the single parameter change (32.32%; sign test, N = 12, p < .05). For all 12 participants, the incidence of double parameter changes was lower than that of the quasi-double parameter changes (39.57%; sign test, N = 12, p < .001), whereas the incidences of the single and quasi-double parameter changes were statistically indistinguishable (sign test, N = 12, ns). The results at the highest movement speed were comparable with those for the 4-Hz mode. All 12 participants produced fewer double than single (24.00% vs. 36.61%) parameter changes (sign test, N = 12, p < .001) or quasi-double (36.48%) parameter changes (sign test, N = 12, p < .001), whereas the percentages of single and quasi-double parameter changes were statistically indistinguishable at the highest movement speed (sign test, N = 12, ns).

Last, the bottom panel of Figure 5 shows the incidence of various types of parameter changes that immediately followed \(A^+F^+\) and \(A^-F^-\) performance errors. We have isolated that subset of the data because the parameter changes that followed those errors were not solely the result of natural biomechanical tendencies. In other words, we considered the double parameter changes under those conditions a reflection of deliberate control. The bottom panel of Figure 5 shows the incidence of single parameter changes, double parameter changes that reduced both the amplitude and frequency errors (double), double parameter changes that increased both the amplitude and frequency errors (which we have labeled drift), and quasi-double parameter changes. As expected, double parameter changes that reduced both the amplitude and frequency error at the lowest tempo (1 Hz) outnumbered the other parameter changes. More specifically, for 10 of the 12 participants the incidence of double parameter changes (14.75%) at the lowest tempo was higher than the incidence of quasi-double parameter changes (10.85%; sign test, N = 12, p < .05). The incidence of double parameter changes was higher for all 12 participants than were the incidences of single (6.35%) and drift (1.84%) parameter changes (sign tests, Ns = 12, ps < .001). For all 12 participants, quasi-double parameter changes outnumbered both single and drift (sign tests, N = 12, ps < .001) parameter changes, and single parameter changes outnumbered drift changes (sign test, N = 12, p < .001). In contrast, in the 5-Hz mode, quasi-double (18.45%) and single (18.20%) parameter changes were statistically indistinguishable, whereas both parameter changes outnumbered double (8.19%) and drift (4.09%) parameter changes (sign tests, Ns = 12, ps < .001), with 11 of the 12 participants producing more double than drift parameter changes (sign test, N = 12, p < .05).

### Table 2. Incidence of Parameter Changes (Single, Double, and Quasi-double) as a Function of Categories of Error Change (Increase, Increase and Decrease, and Decrease), as Percentage of the Local Goal Parameter

<table>
<thead>
<tr>
<th>Error change category</th>
<th>Type of parameter change</th>
<th>Single</th>
<th>Double</th>
<th>Quasi-double</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Local goal parameter</td>
<td>Percentage</td>
<td>9.97%</td>
<td>4.48%</td>
<td>8.10%</td>
<td>22.55%</td>
</tr>
<tr>
<td></td>
<td>(\Delta F_{err} = 1%; \Delta A_{err} = 6%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta F_{err} = 5%; \Delta A_{err} = 8%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\Delta F_{err} = 6%; \Delta A_{err} = 9%)</td>
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<tr>
<td></td>
<td>(\Delta F_{err} = 4%; \Delta A_{err} = 8%)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase and decrease</td>
<td>Percentage</td>
<td>14.36%</td>
<td>16.01%</td>
<td>18.04%</td>
<td>48.41%</td>
</tr>
<tr>
<td>Local goal parameter</td>
<td>(\Delta F_{err} = 2%; \Delta A_{err} = 7%)</td>
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<tr>
<td></td>
<td>(\Delta F_{err} = 6%; \Delta A_{err} = 8%)</td>
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<td></td>
<td>(\Delta F_{err} = 6%; \Delta A_{err} = 10%)</td>
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<tr>
<td></td>
<td>(\Delta F_{err} = 4%; \Delta A_{err} = 8%)</td>
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<tr>
<td>Decrease</td>
<td>Percentage</td>
<td>2.31%</td>
<td>9.59%</td>
<td>15.23%</td>
<td>27.12%</td>
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<tr>
<td>Local goal parameter</td>
<td>(\Delta F_{err} = 1%; \Delta A_{err} = 9%)</td>
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<td>(\Delta F_{err} = 6%; \Delta A_{err} = 8%)</td>
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<td>(\Delta F_{err} = 7%; \Delta A_{err} = 10%)</td>
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<td></td>
<td>(\Delta F_{err} = 4%; \Delta A_{err} = 9%)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>Percentage</td>
<td>26.64%</td>
<td>30.08%</td>
<td>41.37%</td>
<td>98.08%</td>
</tr>
<tr>
<td>Local goal parameter</td>
<td>(\Delta F_{err} = 1%; \Delta A_{err} = 7%)</td>
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<td></td>
<td>(\Delta F_{err} = 6%; \Delta A_{err} = 8%)</td>
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<td>(\Delta F_{err} = 6%; \Delta A_{err} = 9%)</td>
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<td>(\Delta F_{err} = 4%; \Delta A_{err} = 8%)</td>
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</table>

*Note.* The mean percentage parameter change size—local frequency error change and local spatial error change (\(\Delta F_{err}\) and \(\Delta A_{err}\), respectively)—are specified in parentheses.
Discussion

In this study, we were concerned with the means by which people vary parameters of movement relevant to achievement of a task goal. Our principal aim was to distinguish parameter changes that reflected the exploitation of biomechanics from those that required deliberate control. Pursuing that logic, we found that most movements (41.37%) were quasi-double parameter changes and, as such, can be said to have resulted from exploiting (or following) natural biomechanical tendencies. The high incidence of such changes is, of course, consistent with Bernstein’s (1967) influential view that adaptive motor behavior entails exploitation of, rather than resistance to, physics. Fewer movements (26.64%) resulted from single parameter changes. Most important for this study, an appreciable number of movements (30.08%; Table 2), which we interpret as a reflection of deliberate control because the resulting movements entailed the overriding of natural amplitude–frequency relationships.

That the relative frequencies of the different kinds of parameter changes reflected strategic influences was supported by the dependence of the parameter changes on movement speed. As seen in the top panel of Figure 5, at low movement speed (1 Hz), participants could produce double parameter changes as often as quasi-double parameter changes, with single parameter changes occurring the least often. By contrast, at high movement speed (5 Hz), when deliberate control was presumably harder, participants produced more single and quasi-double parameter changes than double parameter changes. Those results confirm our prediction that double movement-parameter changes would outnumber the other parameter changes at low movement speed, (bottom panel in Figure 5) and that quasi-double and single parameter changes would outnumber double parameter changes at higher movement speeds.

How successful were the observed parameter changes? As we have just reported, participants produced more movements that reduced either one or both parameter errors than movements that led both local movement parameters to drift away from the goal parameter combination (75.53% vs. 22.55%). Moreover, early in the trials, errors were large, but the size of the error was substantially reduced over subsequent movements (Figure 3). Amplitude errors were, on average, almost 3 times larger than frequency errors, and the ratio between both errors remained approximately constant over movement cycles. Those observations indicate that participants were more tolerant of amplitude errors than of frequency errors, perhaps because of differences in acuity for the two kinds of signals. The difference between frequency and amplitude errors could also be associated with competition for visuomotor resources (i.e., processing information about the cursor position and using that information to control the limb).

Furthermore, with regard to movement amplitude, participants typically produced more undershoots than overshoots,
which is reminiscent of other smaller-than-required amplitudes in studies of aiming and is possibly indicative of a strategy in which participants gradually decrease the percentage of undershoots and “sneak up” on the target as part of a “play-it-safe” approach (see Elliott, Hansen, Mendoza, & Tremblay, 2004; Engelbrecht, Berthier, & O’Sullivan, 2003). The strategy of sneaking-up on the target corresponds to the notion of attempting to reduce travel costs in movement (see Rosenbaum et al., 1995, for further discussion and simulations). Relatedly, a control analysis of between-trial error reduction revealed that participants mainly realized offline parameter changes at lower movement speeds and chiefly changed movement amplitude (see Figure 4). In those cases, the error reductions were considerably smaller than the within-trial performance improvements.

Must individuals use deliberate control to do what is unnatural? It is tempting to suppose that individuals need an act of will to initiate a gait whose frequency departs from the walking eigenfrequency or to begin oscillating the two index fingers at a relative phase other than 0° and 180°. However, spontaneous variation may account for such departures from natural values, making it unclear whether the departures are statistical oddities rather than deliberate choices. Our strategy in focusing on the control of two variables at once (amplitude and frequency) gives us a way of approaching that difficult problem. Because the two variables we studied have a natural, inverse relation, changes that violate the natural relation are unlikely to result from chance alone. Indeed, if the changes are independent, the likelihood of both variables changing in some joint fashion is given by the product of their probabilities. The likelihood can be even smaller if the pairwise, unnatural changes are dependent. Furthermore, if the changes occur when they are adaptive for goal attainment, then it is hard to imagine that they are not the result of deliberate control (although difficulty of imagination hardly constitutes proof). Nonetheless, assuming that deliberate control occurred in our task, such control presumably reflected internal representations of factors that must be governed (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Swinnen & Wenderoth, 2004).

A final remark is that in this work, we offer a new way of determining when deliberate control comes into play vis-à-vis traditional methods used in cognitive psychology. The traditional method, from Posner and Snyder (1975), is to measure reaction time to detect stimuli that are known to be likely but which are misused or only symbolically cued by immediately preceding signals. Participants in such experiments can direct their attention at will to consciously expected locations. In those experiments, deliberate control is inferred from reaction times and errors in tasks that are mainly perceptual. In the present study, we offer a new way of inferring deliberate control from kinematics in tasks that are mainly motoric.

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NOTES

1. Our predictions would not have been confirmed (a) if participants produced more double parameter changes when the required tempo of movement was fast than when the required tempo of movement was slow or (b) if in high-speed conditions, double parameter changes occurred most frequently when local errors consisted of combined amplitude and frequency overshoots or undershoots.

2. Even though that conservative minimum value may have resulted in an overestimation of the incidence of intended parameter changes, we were careful to test the core hypothesis concerning task-constraint prioritization by comparing data that were independent of threshold variations. In fact, various minimum values were tested, but the results of those analyses all pointed in the same direction, as presently reported, in relation to the 1% criterion.

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