Human control of an inverted pendulum: Is continuous control necessary? Is intermittent control effective? Is intermittent control physiological?

Ian D. Loram[1], Henrik Gollee[2], Martin Lakie[3] and Peter J. Gawthrop[2]

[1]*Institute for Biomedical Research into Human Movement and Health, Manchester Metropolitan University, John Dalton Building, Oxford Road, Manchester M1 5GD, UK*
[2]*Department of Mechanical Engineering, Centre for Systems and Control, University of Glasgow, G12 8QQ, UK*
[3]*Applied Physiology Research Group, School of Sport and Exercise Sciences, University of Birmingham, B15 2TT, UK*

Non technical summary Homeostasis, the physiological control of variables such as body position, is founded on negative feedback mechanisms. The default understanding, consistent with a wealth of knowledge related to peripheral reflexes, is that feedback mechanisms controlling body position act continuously. For more than fifty years, it has been assumed that sustained control of position is best interpreted using continuous paradigms from engineering control theory such as those which regulate speed in a vehicle 'cruise control' system. Using a joystick to control an unstable load that falls over like a person fainting, we show that control using intermittent gentle taps is natural, more effective and robust to unexpected changes than continuous hand contact, works best with two taps per second, and can explain the upper frequency limit of control by both methods. Serial ballistic control, limited to an optimum rate, provides a new physiological paradigm for interpreting sustained control of posture and movement.

Abstract Human motor control is often explained in terms of engineering 'servo' theory. Recently, continuous, optimal control using internal models has emerged as a leading paradigm for voluntary movement. However, these engineering paradigms are designed for high bandwidth, inflexible, consistent systems whereas human control is low bandwidth and flexible using noisy sensors and actuators. By contrast, engineering intermittent control was designed for bandwidth-limited applications. Our general interest is whether intermittent rather than continuous control is generic to human motor control. Currently, it would be assumed that continuous control is the superior and physiologically natural choice for controlling unstable loads, for example as required for maintaining human balance. Using visuo-manual tracking of an unstable load, we show that control using gentle, intermittent taps is entirely natural and effective. The gentle tapping method resulted in slightly superior position control and velocity minimisation, a reduced feedback time delay, greater robustness to changing actuator gain and equal or greater linearity with respect to the external disturbance. Control was possible with a median contact rate of $0.8 \pm 0.3 \, \text{s}^{-1}$. However, when optimising position or velocity regulation, a modal contact rate of $2 \, \text{s}^{-1}$ was observed. This modal rate was consistent with insignificant disturbance–joystick coherence beyond 1–2 Hz in both tapping and continuous contact methods. For this load, these results demonstrate a motor control process of serial ballistic trajectories limited to an optimum rate of $2 \, \text{s}^{-1}$. Consistent with theoretical reasoning, our results suggest that intermittent open loop action is a natural consequence of human physiology.

Introduction

Part of the repertoire of human motor control includes ballistic movements, which are those executed in a pre-programmed manner without being influenced by sensory feedback. Such open loop control is observed during rapid eye movements and during rapid reaching or pointing movements. Discrete reaching movements are initially ballistic (open loop) and moderated by sensory feedback beyond the first few tenths of a second (Wolpert *et al.* 1995; Hinder & Milner, 2003). However, much human control is sustained and apparently continuous in nature. Maintaining balance whether standing quietly or in a more dynamic situation requires ongoing regulation as does controlling the steering wheel while driving or controlling the sail while yachting or windsurfing. When control is sustained, it is not obvious whether control actions can be individualised into discrete actions with a beginning and end: one is always responding to the ever-changing sensory information from the environment without and within. Electrophysiological recordings from individual cells in the cerebellum, and EEG and MEG recordings from the cortex show continuous responses to changes in sensory input. Recordings of EMG, ankle moment and ultrasound show continuous responses to high frequency joint rotations (Evans *et al.* 1983; Rack *et al.* 1983; Cochrane *et al.* 2009). Under these circumstances it is understandable that sustained control has been explained and interpreted within the framework of continuous control theory: optimal control using internal predictive models is currently the dominant paradigm. Sustained control is often investigated using a continuous disturbance signal and the results are usually interpreted using a linear time-invariant model (or slowly evolving linear time-invariant models) (van der Kooij & de Vlugt, 2007; Kiemel *et al.* 2008). Additive or signal-dependent noise is used to account for the variability.

Variability is inherent to human movement (Bernstein, 1967; Faisal *et al.* 2008). It is known that signal-dependent noise is intrinsic throughout the human sensory, processing and muscular system (Harris & Wolpert, 1998); however, variability is thought to encompass more than this. For reactions beyond the simplest of human spinal reflexes, the delay between stimulus and response is variable which reflects the fact that responsiveness to sensory information is not constant. Responses may be triggered by stimuli crossing a threshold requiring action (Asai *et al.* 2009; Resulaj *et al.* 2009); also responses may be constructed and executed in a serial fashion (Loram & Lakie, 2002) in which case sensory information may be assimilated continuously but only responded to at particular times when actions are executed. Both cases fall within the concept of intermittent control which includes event- and clock-driven actions (Gawthrop & Wang, 2009; Gawthrop *et al.* 2010).

There is a history of intermittent control within the motor control literature. In their seminal papers, using manual pursuit tracking of unpredictable, paired discrete stimuli, Craik and Vince showed there was a maximum frequency (2–3 actions per second) at which discrete movements could be made without mutual interference and loss of accuracy. These limitations, attributed to the psychological refractory period, are related to the fact that responses to unpredictable stimuli become delayed when they occur in too rapid succession i.e. more than 2–3 per second (Craik, 1947; Vince, 1948). Responses to predictable stimuli can occur at a much higher rate.

Craik hypothesised that intermittent control, that is the serial production of ballistic actions, was generic to human motor control. This hypothesis excited much interest in the post war period leading to attempts to explain human motor control within a discrete control paradigm (Bekey, 1968; Navas & Stark, 1968; Poulton, 1974). However, beyond the establishment of the psychological refractory period for discrete movements following a target, no concrete evidence supporting 'clock-related' intermittent control in humans has emerged. This question is complicated by the fact, observed by Craik (1947), that with practice humans make their actions smooth thus concealing evidence of inter-mittent control. The strongest circumstantial evidence for intermittent control in humans of this 'clock related' kind is the low bandwidth of voluntary control: coherent tracking of unpredictable stimuli deteriorates beyond 1–2 Hz (Navas & Stark, 1968; Loram *et al.* 2006, 2009).

Engineering controllers are usually continuous. Controlling only intermittently and having periods when sensory information is not responded to would appear to be throwing away something important. Indeed, disturbance rejection for controllers using discrete sampling (e.g. discrete and intermittent controllers) is inferior to continuous counterparts (Gawthrop, 2009). Experiments studying intermittent control in humans, in the sense of presenting sensory information inter-mittently, show that performance is degraded (Slifkin *et al.* 2000). Unless intermittent control offers advantages over continuous control, humans will seek to control as continuously as their physiological mechanisms allow.

Deciding whether or not human control is intermittent has proven an elusive task (Navas & Stark, 1968; van der Kooij & de Vlugt, 2007). Here we break the impasse by asking whether continuous control is necessary, whether intermittent control is effective and furthermore whether intermittent control is alien or natural to humans. If during what would normally be regarded as a continuous control task, control using an explicitly intermittent ballistic method proves to be entirely natural and effective, then we demonstrate the biological viability of inter-mittent open loop control as a strategy. If participants reveal a characteristic frequency when pushed to optimise

performance using the intermittent method, then we demonstrate the existence of a physiological process.

Since it is well established that peripheral reflexes are continuous in nature we have chosen a task that eliminates proprioceptive and vestibular reflexes. To avoid studying overtly discrete movements we have chosen a task that requires sustained, and in general terms 'continuous', feedback control. We studied compensatory, visuo-manual tracking of an unstable second-order load with an unstable time constant equivalent to that of an upright standing human (Loram *et al.* 2009). Without appropriate feedback, control is lost in a matter of seconds (Loram *et al.* 2006).

Using a joystick, participants were instructed to maintain either continuous manual contact or intermittent contact, controlling the joystick through gentle taps. When controlling through gentle taps, the feedback control loop is open when the hand is not in contact with the joystick. Even though visual feedback was available continuously this method is explicitly intermittent and can be described as 'act intermittently'. It is explicitly a non-stationary (properties vary with time), non-linear process. We also wished to explore the efficacy of control by intermittent contact under a variety of intentional goals including prioritisation of position regulation, velocity regulation or non-intervention. Thus we investigated the effect of contact (continuous *vs.* intermittent) and intention (position *vs.* velocity *vs.* non-intervention).

We address the following specific questions.

(1) Is continuous contact and thus continuous control necessary when controlling an inverted pendulum?
(2) Is control by intermittent contact (act intermittently) (i) natural and (ii) effective?
(3) Does the observed tapping frequency correspond (i) to the frequency of independent ballistic actions identified by Craik (1947, 1948) in relation to the psychological refractory period, (ii) correspond to the frequency beyond which coherence with the unpredictable disturbance is lost during normal control with continuous contact?
(4) Is intermittent control (act intermittently) consistent with known physiology of normal motor control?

Methods

Ethical approval

These experiments were approved by the Academic Ethics Committee of the Faculty of Science and Engineering, Manchester Metropolitan University. Participants gave written, informed consent to these experiments which conformed to the standards set by the latest revision of the *Declaration of Helsinki*.

The apparatus, historical evolution from the study of quiet standing, measurements, methods of analysis and rationale for these methods have already been described in detail (Loram *et al.* 2009). We refer the reader to the previous work and restrict detail here to the minimum necessary.

Procedure

Eleven healthy adults (9 male, 2 female), aged 21–59 years (36 ± 13 years, mean ± S.D.), sat quietly in a self-selected position. Using a sensitive, contactless, uniaxial joystick, participants controlled the left–right position of a dot on an oscilloscope (Fig. 1). As described previously (Loram *et al.* 2009), the dot represented the position of a virtual load running in real time. The joystick position specified the control force applied to the virtual load. The virtual load was also subject to a virtual destabilising gravitational force appropriate for a human inverted pendulum and also to a virtual passive stiffness countering 85% of the virtual gravitational moment. Participants were instructed to maintain either continuous manual contact with the joystick (Fig. 2*A*–*C*) or intermittent contact, controlling the joystick through gentle taps (Fig. 2*D*–*F*). In any one trial, participants were also instructed to prioritise one of three goals: (a) 'minimise position', i.e. keep the load position as close to the centre of the oscilloscope as possible; (b) 'minimise velocity', i.e. keep the load position still, but it does not matter where the load is on the screen; or (c) 'maximise non-intervention', i.e. wait as long as possible before intervening with the joystick to control the load, but keep the load position on the screen.

An additional two experimental trials were performed by eight of the eleven subjects. Participants were asked to control the unstable second-order load, 'minimising position' and using both methods of contact. However, in these trials, unknown to the participants, the gain on the joystick was instantly changed at unpredictable moments in the trial (Fig. 5). Three levels of joystick gain (×1, ×2, ×5) were used; each level was used for the same extent in each trial, but the order of the levels and changes was randomised. There was a possibility of change at the start of each 10 s epoch, though that was not known to the participants.

These six or eight experimental conditions (Table 1) were presented in randomly selected order and participants were asked to balance each load for one trial for 200 s. Since the task required close, continuous attention, a mental break of up to 5 min was offered between trials.

Prior to the experiment, participants were given an opportunity to familiarise themselves with all experimental conditions of the task and gain confidence in their ability to sustain control for 200 s. Control

Table 1. Summary of experimental conditions

| Experimental condition	Goal	Joystick contact	Joystick gain	Label
1	Minimise position	Continuous	Constant	pos 1
2	Minimise position	Intermittent	Constant	pos i 2
3	Minimise velocity	Continuous	Constant	vel 3
4	Minimise velocity	Intermittent	Constant	vel i 4
5	Maximise non-intervention	Continuous	Constant	non 5
6	Maximise non-intervention	Intermittent	Constant	non i 6
7	Minimise position	Continuous	Variable	pos 7
8	Minimise position	Intermittent	Variable	pos i 8

requires the participant to make uniaxial (left and right) adjustments of the joystick typically involving the flexors of the fingers and adductors of the thumb. Whether using continuous or intermittent contact (gentle tapping) the control movements of the joystick were small (a few millimetres).

The familiarisation included an explanation of the effect of the joystick on the load. Participants were told that the position of the joystick modulated the acceleration of the load. They were also told to locate the neutral position of the joystick which applied no effect on the load. For the varying gain trials, it was explained that 'something would change unpredictably', but we did not explain the nature of the change. If the load was occasionally 'dropped' and passed beyond the positional limits of ± 10 V, the load position was automatically returned to the centre with zero velocity within a few tenths of a second. Two participants were experienced inverted pendulum balancers, six had limited previous experience, and three had no previous experience of this task.

Apparatus and measurements

The real-time virtual loads were constructed using Simulink (MathWorks), compiled using Real-Time Workshop and executed on a laptop using Real-Time Windows Target within MATLAB v7 at a sample rate of 1000 samples per second. The unstable second-order load has the unstable time constant of a human 'inverted pendulum' balanced by calf muscle activity acting through a compliant tendon (Lakie *et al.* 2003; Loram *et al.* 2005*a*,*b*) and has been used previously (Load 2, Table 1, Loram *et al.* 2009). The joystick voltage was sampled at 16 bit resolution and used as analogue input to the real-time model.

The participant operated a hand-held contactless single-axis joystick (HFX Magnetic, CH Products Ltd, UK). The internal restoring spring was removed and the rubber surround, providing dust protection, was retained. With the hand in contact the rubber surround provided no appreciable resistance to the hand although the rubber
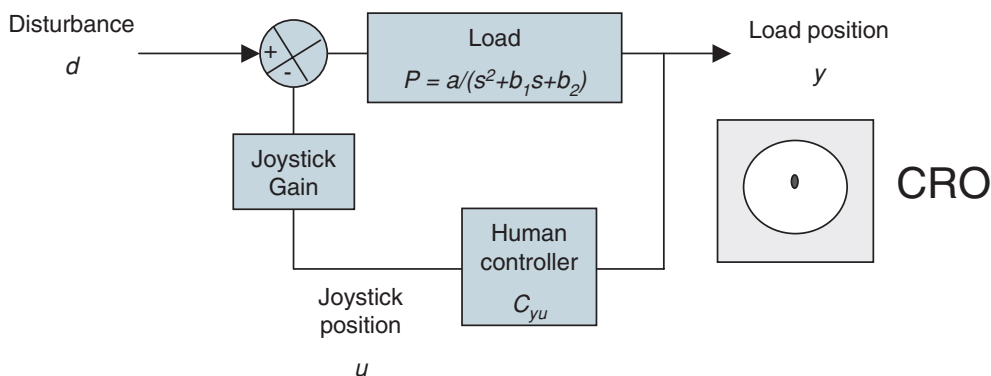
Figure 1. Visually guided manual control of stable and unstable loads
Participants sat at a table, manipulating a table-supported, sensitive, uni-axis joystick with their self-chosen hand. Joystick voltage and a continuous multi-sine disturbance were sampled digitally and applied to a virtual load running in real time in Simulink. Position of the load was displayed 50 cm away on an oscilloscope (CRO) of full scale range, 10 cm. Participants were instructed to use one of two methods: *continuous contact* with the joystick or *intermittent contact* (gentle tapping). The virtual load (P) was second-order unstable with a transfer function $6.977/(s^2 + 0.03721s - 1.231)$ (where s is the Laplace variable) which has an unstable time constant equivalent to that of a standing adult (Loram *et al.* 2009). The human controller (C_{yu}) transfer function can be estimated empirically. Normally the joystick gain was constant. In a secondary experiment, the joystick gain was randomly changed to relative values of $\times 1$, $\times 2$ and $\times 5$.
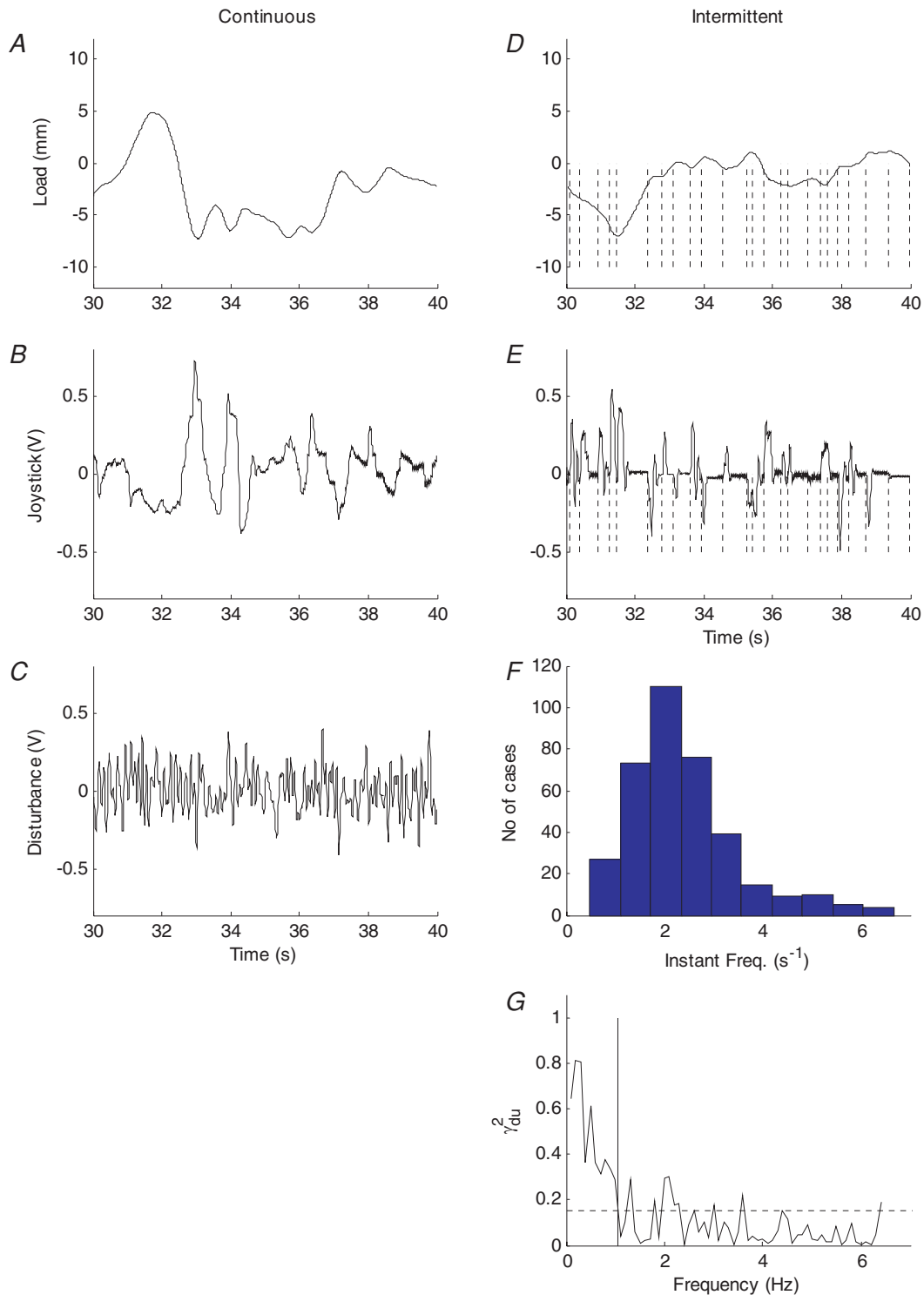
Figure 2. Representative control using continuous and intermittent contact
The subject was instructed to prioritise 'position'. Left panels show continuous contact; right panels show intermittent contact. A disturbance was applied in both cases though only shown for the continuous case. Joystick movement is 2.5 mm V^{-1}. *A*, load position; *B*, joystick position; *C*, external disturbance; *D*, load position; *E*, joystick position. For *D* and *E*, vertical dashed lines show initiation of contact. *F*, incidence of contacts binned according to 'instant frequency', i.e. 1/tapping interval. *G*, coherence between disturbance and joystick. The horizontal and vertical lines show the value of coherence required for significance at 95% confidence, and the frequency at which coherence first passes from significance to non-significance, respectively. Note, this frequency is approximately half the modal contact frequency.

surround provided sufficient restoring force to return the joystick to a neutral position when released. When the joystick was gently tapped or released from a fixed position, the rubber surround gave the joystick a lightly damped response at 7 Hz (Fig. 2*E*). This damped response was used to calculate the onset of intermittent contact. We released the joystick from a number of positions, recorded the damped oscillation and fitted a second-order model. The model gave coefficients for the position and movement energy of the joystick. Intermittent contact (gentle tap) occurs either when the joystick is at rest, or less frequently, while the joystick is still settling from the previous tap (Fig. 2*E*). When the joystick is settling from a previous tap, the total energy of the joystick (position + movement energy) decreases. When given a tap, joystick total energy increases sharply. Thus the onset of intermittent contact was calculated from the joystick signal using the following rules: (a) a cessation of zero velocity of the joystick, and (b) a sharp increase of total energy.

Thresholds were set defining zero velocity and zero velocity (1st derivative) of total energy. Contact initiation was defined when joystick velocity magnitude crossed the threshold following a preceding minimum period (50 ms) of zero velocity, or when velocity of total energy exceeded the positive threshold following a preceding period of 50 ms below the threshold. All intermittent contact trials were verified by close visual inspection as can be done for the example in Fig. 2*E*.

To reveal the feedback time delay we applied an unpredictable external disturbance to the closed loop human-load system and measured the loop delay between the disturbance and the corrective joystick response. The external disturbance was multi-sine, of period 10 s, containing power at frequencies 0.1, 0.2, 0.3 . . . . 10 Hz and with zero mean value. For each trial, the phases were re-randomised, and the crest factor (ratio of maximum deviation to standard deviation) (Pintelon & Schoukens, 2001) was limited to 3. Preliminary experiments showed that coherence between the disturbance and joystick was greatest when the participants were able to maintain close control of the load. The disturbance amplitude was constant for all subjects and set to allow sustained control of the unstable loads. Preliminary work also confirmed that the 10 s periodicity of the external disturbance was not detectable even to informed preliminary participants.

All three signals – load position, joystick position and applied disturbance – were saved at 100 Hz.

Data analysis

For each trial, non-parametric frequency analysis was used to calculate the following quantities:

(1) Power spectra of the disturbance, P_{dd}, and joystick position, P_{uu}, where d and u represent the disturbance and

control signal (joystick position) of the closed loop system (Fig. 1).

(2) Bivariate coherence between disturbance and joystick position, γ^2_{du}.

Taking advantage of the periodic disturbance to produce an exact frequency analysis with no leakage (Pintelon & Schoukens, 2001), we used Welch's averaged, periodogram method with no window and non-overlapping segments of duration 10 s (Halliday *et al.* 1995).

For each trial, the unbiased cross correlation, multiplied by the sampling frequency, was calculated between disturbance and joystick position r_{du}. This measures the statistical association between the two quantities at different time lags, and, because the disturbance approximates white noise, it provides a non-parametric estimate of the closed loop impulse response functions between disturbance and joystick position.

Causal, linear time-invariant analysis. The closed loop relationship between disturbance and joystick position was modelled as a high order, autoregressive moving average (ARMA) process. The ARMA coefficients define the closed loop impulse and frequency response functions between disturbance d and joystick position u.

For the ARMA models we used a sample interval of 50 ms. The model orders, (28 ± 9, mean $\pm$ S.D.) were selected using the Akaike information criterion (AIC). For validation we compared the non-parametric analysis with the equivalent ARMA results. The non-parametric cross correlation was compared with the linear time-invariant (LTI) impulse response function. In a second step, we tested whether the prediction errors (residuals) of the ARMA models are independent of each other and of the disturbance using the 'independence' and 'whiteness' tests. From the 66 ARMA models (11 participants, 6 conditions), 64 passed the whiteness test and 49 passed the independence test without violation. Since the violations in the remaining models were so minor, and the impulse response function compared well with the cross correlation function, all models were accepted.

From the ARMA models relating disturbance to joystick position we calculated: (a) the closed loop impulse response function g_{du} and (b) the open loop, visuo-manual transfer function of the human controller C_{yu} (using the known load transfer function).

Calculation of feedback time delay. As previously (cf. Fig. 3*F* in Loram *et al.* 2009), we calculated the feedback time delay from the closed loop impulse response function g_{du} relating disturbance to joystick and also from the cross correlation function r_{du}. Both values were used for cross checking; the former are presented.

Statistical analysis

Following data analysis, the main measures of interest for group analysis were the root mean square (r.m.s.) load position, r.m.s. load velocity, feedback time delay, median tap interval, modal tap interval (1/instant frequency), and frequency at which coherence first passes from significant to non-significant. Unless stated otherwise, quantities were tested for differences according to experimental condition using the Kruskal–Wallis, non-parametric analysis of variance. Unless stated otherwise, individual values are quoted as a median $\pm$ interquartile range.

Clarification of terms. *Frequency*. Although we attempt to avoid confusion, the term frequency is used in three different senses in this paper. In the statistical sense, frequency distribution (Figs 2*F* and 4*A* ordinates), we refer to the number of occurrences in different bins. In the signal processing sense, we refer to the frequency of a periodic signal in Hz (Figs 2*G*, and 4*B*, *C* and *F*). In the instantaneous rate sense, we refer to the reciprocal of a time interval in s^{-1} (Figs 2*F*, and 4*A* and *E* abscissa).

Observation. We mean the estimation of load position and velocity (and all other states such as joystick position) based on all accumulated sensory information.

Sampling. This term is used in three senses. For data acquisition we refer to the sample rate (1000 s^{-1}) of the MATLAB–Simulink environment. For ARMA analysis of data we used a sample rate of 20 s^{-1}. For inter-mittent control by humans or machines, at the point of intermittent ballistic action the current estimate of load position and velocity is used to construct the control action. In the context of intermittent action we refer to this as sampling. An intermittent output, executed open loop, represents the conclusion of a sampling stage (Gawthrop *et al.* 2010) thus the intermittent output frequency is the same thing as the intermittent sampling frequency.

Results

During familiarisation, prior to instruction, most subjects self-selected continuous contact with the joystick. However, when asked to control using gentle taps, all subjects adopted this method with ease and became accomplished within minutes. A few volunteered that they found control by tapping easier. None volunteered that control by continuous contact was easier. Using both methods, and with only a single familiarisation session of 15 min, all subjects were able to control the unstable second-order load in the presence of the disturbance, within the limits of the oscilloscope screen for 200 s.

Representative control using continuous and intermittent contact

Figure 2 shows representative position regulation of the virtual inverted pendulum using continuous manual contact with the joystick (Fig. 2*A–C*) or intermittent contact, controlling the joystick through gentle taps (Fig. 2*D–G*). In both cases, regulation of position was effective (Fig. 2*A* and *D*) confining the load within a few millimetres of the central position. Typically, control by tapping (Fig. 2*D*) was comparable or marginally better than using continuous contact (Fig. 2*A*). Participants showed some initial variation in the tapping strategy they used. Some explored very rapid tapping as well as less frequent tapping. Some explored hard tapping as well as gentle taps. Rapid tapping and hard tapping were usually abandoned as performance became more experienced. This normative example, shows gentle tapping movements of the joystick (Fig. 2*E*) that were similar in size to the joystick movements during continuous contact (Fig. 2*B*). The taps can be seen as abrupt changes of joystick position after a period of joystick stillness (e.g. 34.8 s, Fig. 2*E*) or while the joystick is still showing damped oscillation following the previous tap (e.g. 31.5 s). During continuous contact (Fig. 2*B*) there are also examples of abrupt joystick movement preceded by more stationary periods (e.g. 31 s, 32.5 s). Using intermittent contact, participants typically made taps once, twice or three time per second (Fig. 2*F*), associated with reduced disturbance–joystick coherence beyond 1 Hz (Fig. 2*G*). (N.B. if regular sampling associated with intermittent ballistic action occurred at 2 Hz, we expect significant coherence up to 1 Hz.)

Participants were successful in prioritising different goals

In any one trial, participants were instructed to focus on one of three goals: (i) minimise 'position' i.e. deviation from the centre (conditions 1 and 2); (ii) minimise 'velocity' i.e. don't care about position on the screen but keep the dot still (conditions 3 and 4); (iii) maximise 'non-intervention' i.e. maximise the duration for which the joystick is not used (conditions 5 and 6).

Considered as a group, participants were successful in achieving these goals. When instructed to mini-mise 'position', root mean square (r.m.s.) deviation from the centre (Fig. 3*A*) was reduced significantly from 9 ± 3 to 3 ± 1 mm (median $\pm$ interquartile range), (cases 1–2 *vs.* 3–6, $n = 66$, probability (p) $= 2 \times 10^{-9}$). When asked to minimise 'velocity', r.m.s. load velocity (Fig. 3*B*) was reduced significantly from 11 ± 4 to 5 ± 1 mm s^{-1} (3 and 4 *vs.* 5 and 6, $n = 44$, $p = 2 \times 10^{-7}$). And

when asked to maximise 'non-intervention' (Fig. 3*C*), the median duration between taps was increased significantly from 0.45 ± 0.2 to 1.2 ± 0.4 s (2 and 4 *vs.* 6, $n = 33$, $p = 4 \times 10^{-6}$).

Goals were achieved more effectively using intermittent contact

Contrary to what might be expected, control of the virtual load was slightly superior using intermittent rather than
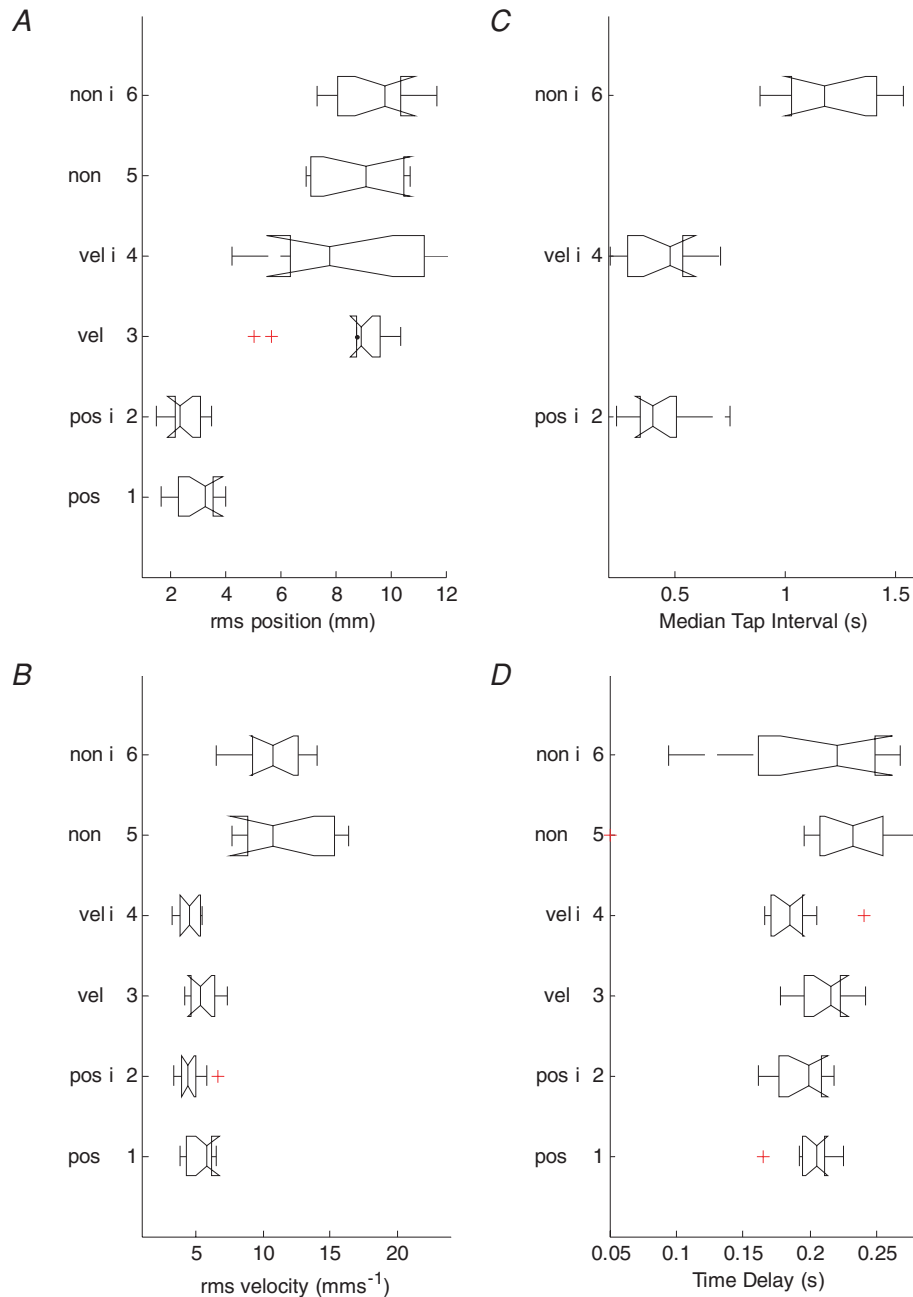

Figure 3. The effect of intermittent *vs.* continuous contact on position control, velocity control, time delay and tap interval
Results are shown for eleven participants, grouped by experiment condition. (1) Min position, continuous contact. (2) Min position, *intermittent contact*. (3) Min velocity, continuous contact. (4) Min velocity, *intermittent contact*. (5) Max non-intervention, continuous contact. (6) Max non-intervention, *intermittent contact*. *A*, root mean square (r.m.s.) load position. *B*, r.m.s. load velocity. *C*, contact interval. *D*, feedback time delay. The box centres, notches, edges, whiskers and crosses show median, confidence in median, interquartile limits, range and outliers, respectively.

continuous contact. When participants were instructed to minimise 'position' or minimise 'velocity' (Fig. 3B, cases 1–4) the velocity of the load was significantly and more consistently lower when participants were instructed to use intermittent (4.4 ± 1 mm s^{-1}, cases 2 and 4) rather than continuous (5.5 ± 2 mm s^{-1}, cases 1 and 3) joystick contact ($n = 44$, $p = 0.01$). When instructed to minimise 'position' (Fig. 3A), deviation from the centre was significantly lower using intermittent (2.4 ± 1 mm, case 2) rather than continuous contact (3.3 ± 1 mm, case 1), (Wilcoxon, paired samples, signed rank, $n = 22$, $p = 0.03$).

Using intermittent contact, control was associated with a reduced feedback time delay. When instructed to minimise 'position' or minimise 'velocity' (Fig. 3D, cases 1–4) the feedback time delay, which is the duration between an unpredictable disturbance and first movement of the joystick, was significantly lower when participants were instructed to use intermittent (190 ± 30 ms, cases 2 and 4) rather than continuous (210 ± 30 ms, cases 1 and 3) joystick contact ($n = 44$, $p = 0.003$).

The frequency distribution of gentle taps

We wished to know whether the participants showed evidence of a frequency limit or preferred frequency of intermittent contact with the joystick (Fig. 4A). When prioritising position regulation or velocity regulation, participants showed a well-defined frequency distribution with a modal frequency at two taps per second (Fig. 4A), fewer taps at higher frequency up to a maximum frequency of about seven taps per second, and a second peak at five taps per second. This secondary mode was highly variable between participants, absent in some, and the dominant mode in four trials (Fig. 4E, circled dots). From visual observation of participants, this high frequency secondary mode consisted entirely of repetitive, unidirectional taps. When asked to maximise the duration of non-intervention, there were fewer taps generally with a lower modal frequency at one tap per two seconds (Fig. 4A).

Is the low feedback control bandwidth (1–2 Hz) related to sampling?

In theory, short-duration pulses contain power across a wide frequency range. In this experiment, gentle tapping (cases 2, 4 and 6) was associated with broadband joystick power (Fig. 4B) and controller gain (Fig. 4D) up to 8 Hz. However, high frequency joystick power and controller gain is not meaningfully related to the disturbance. Using both intermittent and continuous contact, coherence between joystick movement and unpredictable disturbance (γ^2_{du}) deteriorated beyond 1–2 Hz (Fig. 4C).

We wanted to know which factors lead to the low control bandwidth, i.e. the frequency at which coherence is lost. The frequency beyond which coherence (γ^2_{du}) first became non-significant (e.g. Fig. 2G) was not different between intermittent and continuous contact trials (cases 2, 4 and 6 vs. 1, 3 and 5, $n = 66$, $p = 0.45$), but was lower when non-intervention was prioritised (cases 5 and 6 vs. 1, 2, 3 and 4, $n = 66$, $p = 0.02$) (Fig. 4D). Thus the control bandwidth is related to the non-intervention goal, in which participants waited as long as possible before intervening, not the method of contact.

We wanted to know whether the frequency at which coherence was lost could be related to the rate of intermittent gentle taps. Using intermittent contact, the frequency beyond which coherence (γ^2_{du}) first became non-significant, was associated with the modal contact frequency (Pearson, $n = 29$, $p = 1 \times 10^{-8}$, $r^2 = 0.71$), and was associated with the median contact frequency (Pearson, $n = 29$, $p = 5 \times 10^{-10}$, $r^2 = 0.77$) (Fig. 4E). N.B. this result excludes four trials, shown in Fig. 4E, for which tapping was predominantly at 4–5 s^{-1}. Intermittent ballistic action means that a 'switch' is opened in the feedback loop at each action which implies that accumulated sensory information is sampled at each action. For a regular, intermittent controller, significant coherence would be limited to half the intermittent frequency: this is shown as the red line in Fig. 4E for the case where each ballistic action comprises a single contact. The regression lines fitting modal and median contact frequencies lie just above and just below the theoretical line relating sampling frequency to the frequency at which coherence becomes non-significant, respectively (Fig. 4E). The low bandwidth is closely related to sampling on a one contact per ballistic action basis, except when high frequency (4–5 s^{-1}) tapping is dominant.

The mean modal tapping frequency of 2 s^{-1} is also manifest in the open loop control gain (Fig. 4F) which shows the ratio of joystick movement to changes in load position shown on the oscilloscope. For both continuous and intermittent contact, gain increases smoothly and consistently to 2 Hz indicating differential control action. Beyond 2 Hz, gain shows high variability between subjects: when contact is continuous, gain decreases; when contact is intermittent, gain shows an initial decrease (green, cyan, yellow) shortly followed by an increase. Consistent visuo-manual feedback control is limited to 1–2 Hz irrespective of the contact method.

Control by intermittent contact appears linear at low frequency

In system identification analysis, coherence between disturbance and response is traditionally taken as a measure of linearity (see p. 52 in Pintelon & Schoukens,
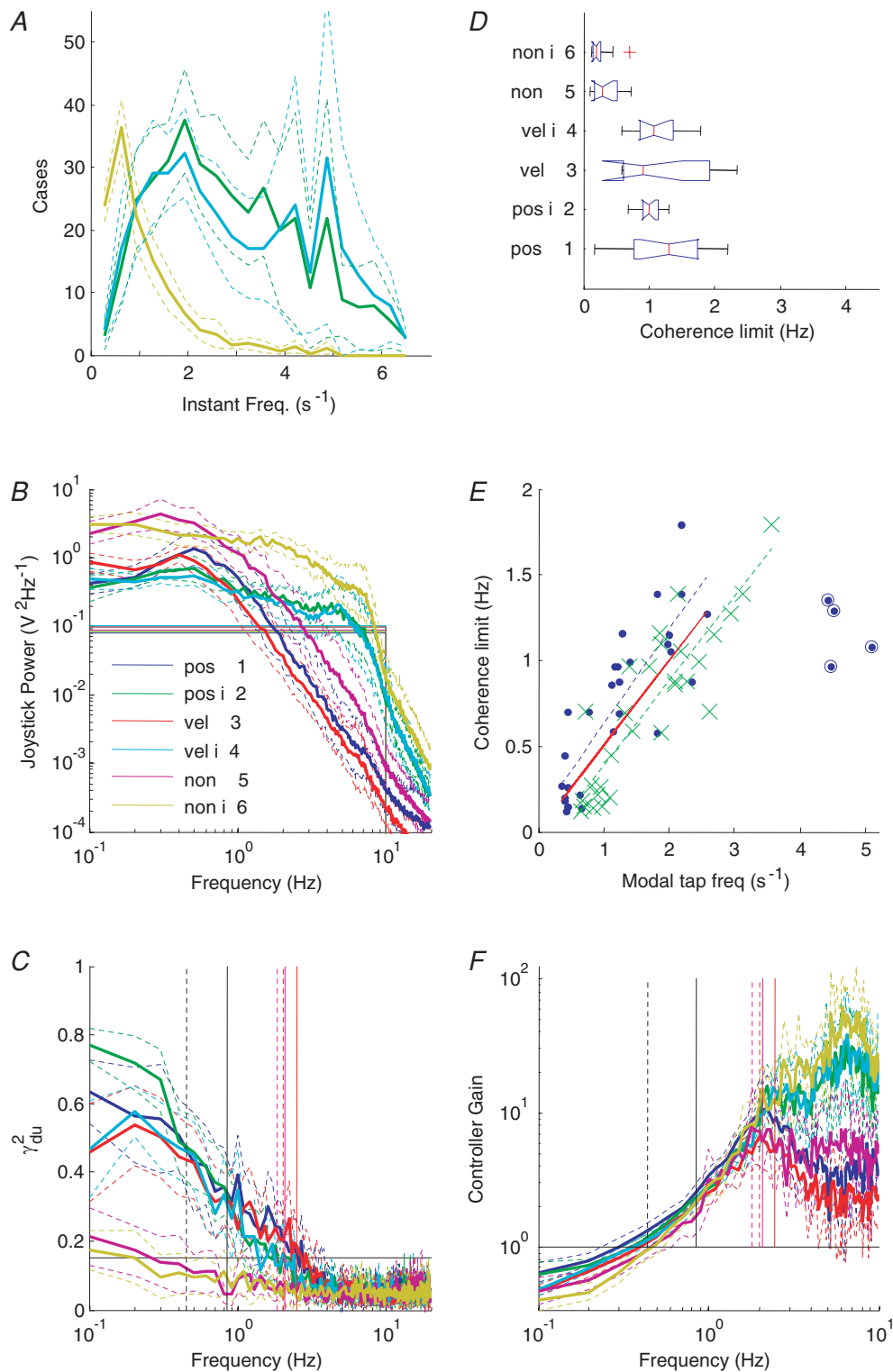
Figure 4 The bandwidth of visuo-manual control
A, incidence of contact during 190 s, binned according to instant frequency (1/contact interval). *B*, joystick power and external disturbance power (straight line up to 10 Hz). *C*, coherence (γ^2_{du}) between joystick and unpredictable external disturbance; the horizontal line is the value of coherence required for significance at 95% confidence. *D*, coherence limit, i.e. frequency at which coherence (γ^2_{du}) first passes from above to below value required for significance; experimental conditions same as Fig. 3. *E*, coherence limit *vs.* modal contact frequency (blue) and *vs.* median contact frequency (green). Shown for intermittent contact trials from all three goals – position, velocity,

2001). However, for each goal (cases 1 *vs.* 2, 3 *vs.* 4 and 5 *vs.* 6) control by intermittent tapping (Fig. 2*E*), which is a non-linear, non-stationary process, shows equal coherence to that using continuous contact. At low frequency (0.1–0.3 Hz) and when position regulation is prioritised, coherence is higher using intermittent contact (Fig. 4*C*, 2 *vs.* 1). Intermittent control appears linear below the modal contact frequency and within the human control bandwidth.

Control by intermittent contact is more robust

In the additional experiment, participants were asked to minimise position, but unexpectedly, the joystick gain was instantly changed, by differing amounts at specific times (Fig. 5). Typically, when contact was continuous (equivalent to condition 1), changes in joystick gain disturbed control causing large oscillations and at times irrecoverable losses of balance (Fig. 5*A–D*). When contact was intermittent (equivalent to condition 2), the disturbing effect was greatly reduced (Fig. 5*E–H*); participants adjusted their tapping after the first unexpected result with little or no oscillation (Fig. 5*G* and *H*).

Considering all participants, when using intermittent contact, deviation from the centre was significantly lower (4 ± 1 mm) than using continuous contact (36 ± 46 mm) (Wilcoxon, paired samples, signed rank, $n = 16$, $p = 0.03$).

Discussion

Intermittent and continuous contact

When the hand is not in contact with the joystick, the participant continues to observe the motion of the load, but this sensory information has no effect: the feedback loop is open. The feedback loop is only closed intermittently when a gentle tap is made. Thus control using intermittent contact consists of serial ballistic actions and is explicitly of the form 'act intermittently'. Since visual information was available continuously we describe this form of control as 'observe continuously, act inter-

mittently'. This phrase distinguishes the experiment from those in which sensory information is presented intermittently (Slifkin *et al.* 2000). The nature of control using continuous contact is more ambiguous. One hypothesis is that control is constructed as a series of ballistic trajectories (Craik, 1947; Hanneton *et al.* 1997; Loram & Lakie, 2002; Loram *et al.* 2005*b*, 2006), possibly modelled as engineering intermittent control (Gawthrop & Wang, 2009; Gawthrop *et al.* 2010); more commonly it is assumed (Maurer & Peterka, 2005; van der Kooij & de Vlugt, 2007; Kiemel *et al.* 2008) that feedback control is continuous.

Unambiguous results

From this experiment, controlling one unstable, virtual inverted pendulum with a relatively sluggish time constant equal to the partially, passively stabilised, standing human (Loram *et al.* 2009), the following firm conclusions can be drawn.

(1) Continuous contact and thus continuous control is not necessary when controlling this inverted pendulum (Figs 2 and 3). All participants maintained control without using continuous feedback. When intended, participants could restrict contact to a median interval of 1.2 s without losing control (Fig. 3*C*) although the best regulation was achieved with contact at a mean interval of 0.45 s.

(2) Intermittent control (observe continuously, act intermittently) is both natural and effective. Participants were able to control intermittently with little familiarisation: moreover, regulation of both position and velocity were superior and the time delay reduced using this method.

(3) When using intermittent contact to provide the best regulation (position or velocity) the modal contact frequency was two taps per second, a secondary mode was observed at 5 s^{-1}, and minimal tapping was observed beyond $5–6 \text{ s}^{-1}$ (Fig. 4*A, C* and *D*).

(4) For control using both intermittent and continuous contact, coherence between the joystick and unpredictable disturbance deteriorates beyond 1–2 Hz.

---

non-intervention. Four trials were excluded (blue circles), on the grounds that the high frequency mode ($4–5 \text{ s}^{-1}$) dominated the low frequency mode at around 2 s^{-1}. The red line shows the predicted relationship (Nyquist sampling frequency) between the coherence limit and modal contact frequency if contact occurred only at the modal frequency. *F*, open loop controller gain spectra. For panels *A, B, C* and *F*, all curves show variation of the quantities with frequency, for each experimental condition, averaged over eleven trials (one from each subject). Dashed lines show 95% confidence intervals in the mean. The experimental conditions for these panels are blue: position, continuous contact; green: position, intermittent contact; red: velocity, continuous; cyan, velocity, intermittent; magenta: non-intervention, continuous; yellow: non-intervention, intermittent. For panels *C* and *F*, vertical continuous and dashed lines show the median and modal contact frequencies, respectively, for intermittent contact trials.

Significance of the modal contact frequency

The modal contact frequency of two taps per second is significant in several respects.

First it corresponds to the frequency of independent ballistic actions (two per second) identified by Craik in relation to the psychological refractory period and unpredictable stimuli (Craik, 1947, 1948; Vince, 1948). Craik showed that actuation of a second discrete tracking movement was delayed and control of both the first and second movement was disrupted unless an interval of approximately half a second elapsed between one discrete tracking movement and a subsequent movement (Vince, 1948). The modal contact frequency observed here supports the idea that compensatory control of a virtual inverted pendulum by intermittent contact is subject to the same psychological refractory period. Thus, for the unstable, second-order load, two ballistic actions per second represents an optimum, modal frequency for accurate control; following Craik's observation of disruption, more frequent control actions would be expected to degrade accuracy.

Second, previous work showed that participants adopted a modal frequency of two to three joystick movements per second when continuously manipulating a joystick to control a real inverted pendulum. When load instability was increased, participants were unable to compensate by increasing the modal frequency of hand movements, as required if control were attained by adjusting the feedback gain (Loram *et al.* 2006) according to impedance regulation theories.

Third, during quiet standing, which requires control of a real inverted pendulum (the human body) using the calf muscles, changes in length of the calf muscles showed the same modal frequency of two to three impulses per
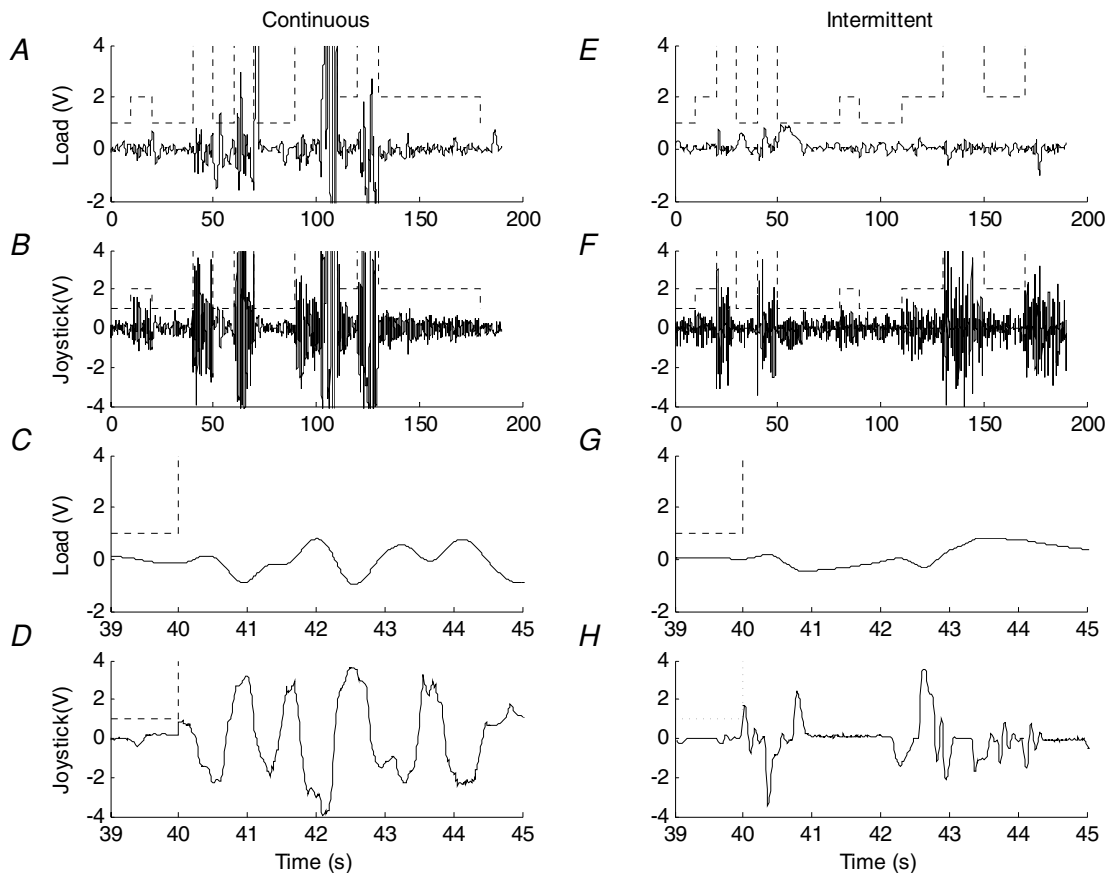

Figure 5. Representative effect of varying joystick gain with intermittent and continuous contact
The participant was controlling the second-order unstable load with 'position' as the goal. Continuous and intermittent contact is shown in left and right panels, respectively. *A, C, E* and *G*: load position (continuous line), joystick gain (dashed lines), *B, D, F* and *H*: joystick voltage after applying joystick gain (continuous), joystick gain (dashed). Load and joystick movement are 20 mm V^{-1} and 2.5 mm V^{-1}, respectively. Joystick gain is quoted relative to normal gain in conditions 1–6, Figs 1–4. Upper two rows show 190 s duration. Lower two rows show one illustrative change in joystick gain. Note how the gain changes at 40 s, the hand is in contact in both cases, and the change in gain causes deviation of the load which is subsequently responded to. Uncorrected oscillation occurs with continuous but not intermittent contact.

second related to control of the centre of mass (Loram *et al.* 2005*b*).

These three observations are consistent with the hypothesis (Craik, 1947; Vince, 1948), that control via serial ballistic actions at a modal rate of two to three per second is generic to human motor control. They provide some unity between visuo-manual tracking and spontaneous postural control.

What is the relationship between coherence (γ_{du}^2) and the frequency of contact?

Control by gentle tapping is overtly intermittent: at the instant of contact, control is ballistic; the accumulated sensory information cannot influence the control action again until the next contact. If each contact is planned independently, the intermittent sampling frequency equals the contact frequency. If some taps are planned and executed in groups of two or more, then the intermittent sampling frequency is less than the contact frequency. With intermittent control, provided sampling is not rationally related to the periodic disturbance, coherence between the disturbance and control signal (γ_{du}^2) deteriorates significantly for frequencies beyond half the sampling frequency (Navas & Stark, 1968). A distribution of intermittent intervals, which by nature is non-periodic and unsynchronised with the disturbance, will degrade coherence in a complex fashion, i.e. not beyond a unique frequency.

For control by intermittent contact, where control is explicitly intermittent, we can relate the upper frequency limit of significant coherence to the maximum intermittent sampling frequency. From the Nyquist sampling theorem, a coherence limit of 2–2.5 Hz (Fig. 4*C*) suggests a maximum intermittent sampling frequency of 4–5 Hz with a corresponding minimum intermittent interval of 200–250 ms. A minimum sampling interval of 200–250 ms is consistent with: (i) the increase in delay of the second *versus* first response to closely paired, discrete stimuli (Vince, 1948; Navas & Stark, 1968), (ii) the simple form of predictive intermittent control which requires that the minimum intermittent interval is equal to the feedback time delay (Section 4.2 in Gawthrop & Wang, 2007; Gawthrop *et al.* 2010) which in this case is approximately 200 ms for the second-order load (Fig. 3*D*, and Loram *et al.* 2009), (iii) a secondary tapping mode at 5 s^{-1}, with relatively sharp roll-off beyond 5 s^{-1}.

However, as mentioned above, tapping at the maximum rate is not optimal and appeared to lessen with experience. The best regulation was associated with a preferred, modal intermittent interval of 0.45 ± 0.2 s (cf. Fig. 4*A* and Fig. 3*C*) and for individual trials the modal interval was associated with deterioration in coherence at approximately half the modal tapping frequency (Figs 2*G*

and 4*E*). When best regulation is not required, the intermittent interval can be even longer (Fig. 3*C*) allowing greater variability of control (Fig. 4*C* and *D*). For control by intermittent contact, there is a clear relationship between intermittent interval and coherence.

Is control by continuous contact subject to intermittent sampling?

The unanswered question is whether control using continuous contact also proceeds via serial ballistic actions. For the second-order load, it is intriguing that the coherence frequency limit is very similar between continuous and intermittent contact (Fig. 4*C* and *D*). If one accepts that for intermittent contact, the coherence limit is a product of sampling, it is logical to conclude the same is true for control by continuous contact. If this reasoning from coherence data is correct, control by continuous contact proceeds by serial open loop actions, with a minimum intermittent interval of approximately 200 ms (from Fig. 4*C*), and a modal intermittent interval of approximately 0.5 s (from Fig. 4*D*, cases 1 and 3 *vs.* 2 and 4). Verification of this would benefit from knowing the onset instances of intermittent, open loop joystick movements during continuous contact. While this information is not available, observation of the joystick movement shows discontinuities (Fig. 2*B*), which may indicate imperfect joining of serial actions. This argument is supported by observation of manual pursuit tracking of ramp and sine targets which show discontinuities at a modal interval of 0.5 s (Navas & Stark, 1968).

Why is control using intermittent contact so effective, even superior to control by continuous contact?

It is surprising that control using intermittent contact is so effective. During the contactless period errors from the previous tap and the external disturbance accumulate without the possibility of correction using sensory feedback. When the load is unstable, these errors accumulate exponentially through time. Thus, continuous feedback is normally understood to be more effective than intermittent feedback.

However, intermittent periods of zero control activity, offers four powerful advantages: it (i) provides temporary elimination of noise associated with executing a motor action, (ii) provides known periods when the load is not influenced by control action which allows clearer observation of the system being controlled, (iii) allows abrupt, higher frequency control stimulation, and (iv) allows economical, fatigue-resistant control.

(i) Biological control is inherently noisy (Harris & Wolpert, 1998; Bays & Wolpert, 2007). During

manual contact, movement of the load is determined by hand movement and the external disturbance (Fig. 1). This manual control contains appropriate and inappropriate movements (motor noise). When there is no joystick contact, hand movement and its motor noise are not transmitted to the load. For example, when joystick gain was changed instantly, this transmitted an unpredicted disturbance to the load only when the hand was in contact (Fig. 5). Generally, intermittent control with periods of no control action would be a sensible approach when low frequency motor noise is the dominant source of destabilisation.

(ii) During continuous contact, the participant cannot distinguish movement of the load resulting from the external disturbance, appropriate hand movement, or inappropriate hand movement (motor noise). The participant applies a feedback gain tuned through experience. The instant change in joystick gain made hand movements largely inappropriate leading to oscillation (Fig. 5*D*) or loss of balance (Fig. 5*A*).

With intermittent contact, a motor action is only applied during a short period of time. (a) Intermittent contact results in known periods when an impulse is generated and the effect is seen instantly on the load as a change in velocity related to the strength of the tap. This clear temporal association makes it easier to develop an internal model of the relationship between hand movement and load. (b) Intermittent contact results in periods between taps when it is known that the load is only influenced by external disturbances. During these known periods it is easier to formulate an internal model of the statistical properties of the disturbance (e.g. size and variability). It is also easier to anticipate future load position. Estimating current load position is unaffected by unknown, inappropriate joystick movement (motor noise). Predicting future load position is simplified by avoiding the need to calculate the effect of current joystick movement on the load. With intermittent contact, changes in joystick gain (Fig. 5), can be easily detected and appropriate adjustments can be made to the next tap.

Periods of no control action would be a sensible approach when the system changes or when muscle properties change. These conditions might apply during assisted, artificial control of muscle during spinal cord injury, where muscle properties are not stable (Gollee *et al.* 2004) and during postural conditions when muscle thixotropy is significant such that muscle properties depend on the recent history of movement (Lakie & Robson, 1988; Campbell & Lakie, 1998; Loram *et al.* 2007).

(iii) It is difficult to observe the dynamics of a closed loop system from steady state or low frequency excitation. When contact is intermittent, it is possible to have impulsive actions, like tapping, which excite higher frequencies of the system which provide more information.

(iv) Intermittent contact allows the possibility of a computational or muscular recovery period between the serial execution of control actions. This is consistent with the principle of making no more computational or muscular effort than necessary.

When would intermittent rather than continuous control be the strategy of choice?

Control using intermittent contact, which we have just discussed, is a special case of intermittent open loop control. Generally, intermittent open loop control (observe continuously, act intermittently) proceeds via serial actions which are pre-planned using accumulated sensory feedback and executed ballistically (Gawthrop & Wang, 2009). These actions need not have periods of zero control activity and can join smoothly: gentle tapping is a special case.

Intermittent open loop control was designed for bandwidth-limited applications where online time delays rule out continuous control (Ronco *et al.* 1999; Gawthrop & Wang, 2006, 2009). For example, an intermittent interval can provide time to complete calculations required to construct a control action or time to send/receive information over a long transmission line. Intermittent control simplifies prediction when the intermittent interval is greater than or equal to the time delay (Section 4.2 in Gawthrop & Wang, 2007; Gawthrop *et al.* 2010).

In general, even with continuous motor output, open loop intervals are ideal for building an understanding (system identification) of the relationship between the load input (ultimately neural output or muscle activity) and load output (movement) (Fig. 1). When the feedback loop is closed as during continuous control, causality between load input and load output become ambiguous – it is unclear whether the relationship between load input and load output represents properties of the load or those of the human controller (van der Kooij & van der Helm, 2005). When the feedback loop is open, even intermittently, causality between measured load input and measured load output is unambiguous and the controller can be improved.

Does human motor control lend itself to intermittent open loop control?

Continuous controllers are ideal when the control bandwidth is high, delays in the system are low, and sensor-actuator noise is relatively low at the (low) frequencies where external disturbances are present and

are to be rejected. Peripheral, reflexive mechanisms are known to be high bandwidth and continuous in nature (Evans *et al.* 1983; Rack *et al.* 1983). However, even for simple tasks, higher-level human physiological control contains significant online feedback time delays related to the complexity of the load controlled: for example, approximately 200 ms for visuo-manual control of second-order loads (Fig. 3*D*), (Loram *et al.* 2009). Moreover, vestibular, proprioceptive and visual sensory systems, and also the neuromuscular system are all intrinsically noisy and contain high variability at low frequencies within the bandwidth of physiological control (Harris & Wolpert, 1998; Bays & Wolpert, 2007). For example, the majority of authors who have studied human standing (control of a second-order unstable load), have concluded in various ways that sensori-motor noise or inappropriate torque modulation is the primary source of standing sway (Loram *et al.* 2001; Loram & Lakie, 2002; Mergner *et al.* 2002; Maurer & Peterka, 2005; Kiemel *et al.* 2006). Intermittent open loop control is an appropriate solution to online time delays, substantial motor noise and computational-muscular economy.

Intermittent control appears to be a natural biological strategy and would require opening the sensory feedback loop while executing control actions. It is no surprise that flexible, refined control by the higher nervous system relies on inhibition of lower continuous feedback systems, attenuation of sensation during movement (Bays *et al.* 2006; Voss *et al.* 2006), and the reduction of unnecessary muscle activation as skill increases (Bernstein, 1967). While control via serial ballistic actions is naturally suited to higher-level physiological mechanisms, containing significant time delays, it does not follow that individual actions will be easily distinguished. Our results (Fig. 4*C*) demonstrate that below the intermittent sampling frequency, control which was explicitly intermittent appeared normally linear and, as Craik observed (1947), with experience, serial ballistic actions become smoothly joined.

If we are correct in interpreting intermittent open loop control as a natural biological strategy, this insight will prove useful beyond the understanding of physiological control, in application areas such as the development of artificial control using neuroprotheses and functional electrical stimulation.

Whether human control is continuous or intermittent is becoming topical. The default understanding is that control is continuous. Recent work has demonstrated the continuous nature of balance for participants standing on translating platforms (van der Kooij & de Vlugt, 2007). However, we have reservations regarding this analysis. First, one would expect balance control to possess high bandwidth, continuous feedback processes (vestibular, proprioceptive reflexes) as well as higher-level intermittent control. Unravelling the two is not simple.

Second, below the intermittent Nyquist frequency, intermittent, open loop control can be indistinguishable from continuous control (Gawthrop, 2009; Gawthrop *et al.* 2010).

A number of authors have considered intermittent control in humans. Studying visuo-manual tracking, it has been thought that intermittency, characterised by step and hold sub-movements is more likely to be threshold triggered (Wolpert *et al.* 1992; Miall *et al.* 1993; Hanneton *et al.* 1997; Squeri *et al.* 2010) rather than clock related as originally proposed by Craik (1947). Studying human standing, event-driven intermittent control has been proposed, in which control is triggered when state-dependent thresholds are passed (Bottaro *et al.* 2008; Asai *et al.* 2009). Intermittent control following state-dependent thresholds has also been investigated for human stick balancing (Milton *et al.* 2009). We consider that intermittent control, by serial ballistic trajectories, naturally includes triggering related to both temporal processes and thresholds. When thresholds are small, such that they are always exceeded, triggering is related to the intermittent interval governed by the psychological refractory period. When thresholds are large, such that there are durations below and above threshold, they determine the triggering of actions (Gawthrop & Wang, 2009; Gawthrop *et al.* 2010). Here we present novel evidence showing a temporal process and modal frequency to human intermittent control of unstable second-order loads.

Clock-driven intermittency in human motor control has been advocated in the form of Adaptive Model Theory (Neilson *et al.* 1988*a*,*b*; Neilson & Neilson, 2005) and in central intermittency where several authors (e.g. Vallbo & Wessberg, 1993) have identified discontinuities in finger movement as pulsatile central neural control at a frequency of 7–10 Hz. These authors consider intermittency to be high frequency with an intermittent interval of 100 or 50 ms. In contrast to these tremor- and vibration-related phenomena, our results present evidence of a low frequency intermittent control process with a modal rate of two actions per second. Clearly these are different processes.

Low frequency serial ballistic control has been advocated previously in relation to control of an inverted pendulum and human standing (Loram & Lakie, 2002; Lakie *et al.* 2003; Loram *et al.* 2005*b*, 2006; Lakie & Loram, 2006). Control by gentle tapping illustrates this serial ballistic process. Given that visual information was continuously available, we have described this process as observe continuously, act intermittently. Given evidence that sensation is downgraded during movement (Bays *et al.* 2006; Voss *et al.* 2006, 2008), it is physiologically plausible, and consistent with Craik's original ideas (Craik, 1947, 1948), that participants alternate action with perception in a trial and error sequence.

Further questions

Using one relatively sluggish, unstable second-order load, these experiments show the efficacy of serial ballistic control. However, many questions are raised including whether these findings generalise? Are the modal and maximum contact rates determined by intrinsic physiological factors or by load-dependent factors such as the complexity or instability of the system being controlled? Following Loram *et al.* (2006) we predict that the modal frequency will be invariant with stability for second-order loads. Previous data (Fig. 4, Loram *et al.* 2009) showed that for second-order loads the upper frequency limit of significant coherence was relatively invariant with load stability and was not increased when loads were more unstable. However, for first-order loads, coherence was significant up to 4–5 Hz which is twice that of second-order loads and which might imply a higher intermittent sampling frequency. On the other hand, first-order loads require one rather than two taps to achieve a step response (Poulton, 1974; Loram *et al.* 2009). Further investigation is required.

Conclusion

Human intermittent control (observe continuously, act intermittently) of this inverted pendulum is entirely natural, highly effective and robust. Continuous joystick contact, and thus continuous control, is not necessary. Most significantly, we have demonstrated a physiological process of intermittent open loop control. When pushed to optimise position or velocity regulation, participants adopted a modal frequency of two taps per second. This rate is consistent with Craik's observation that, on account of the psychological refractory period, two movements per second is the highest frequency one can make without mutual interference between movements. Using intermittent contact, we have shown that the coherence frequency limit relates to the central contact frequency. Since the frequency at which coherence deteriorates does not depend on the method of contact, this suggests that normal control, using continuous contact, is also intermittent in nature. Human higher-level motor control is noisy with substantial online time delays. Given that intermittent open loop control provides solutions to these issues, we suggest that Craik was correct in proposing the ubiquitous nature of serial ballistic control.

References

Asai Y, Tasaka Y, Nomura K, Nomura T, Casadio M & Morasso P (2009). A model of postural control in quiet standing: robust compensation of delay-induced instability using intermittent activation of feedback control. *PLoS One* **4**, e6169.

Bays PM, Flanagan JR & Wolpert DM (2006). Attenuation of self-generated tactile sensations is predictive, not postdictive. *PLoS Biol* **4**, e28.

Bays PM & Wolpert DM (2007). Computational principles of sensorimotor control that minimize uncertainty and variability. *J Physiol* **578**, 387–396.

Bekey G (1968). Identification of sampling intervals in sampled-data models of human operators. *IEEE Trans Man-Mach Sys* **mms-9**, 138–142.

Bernstein N (1967). *The Co-ordination and Regulation of Movements*. Pergamon Press, Oxford.

Bottaro A, Yasutake Y, Nomura T, Casadio M & Morasso P (2008). Bounded stability of the quiet standing posture: An intermittent control model. *Hum Mov Sci* **27**, 473–495.

Campbell KS & Lakie M (1998). A cross-bridge mechanism can explain the thixotropic short-range elastic component of relaxed frog skeletal muscle. *J Physiol* **510**, 941–962.

Cochrane DJ, Loram ID, Stannard SR & Rittweger J (2009). Changes in joint angle, muscle-tendon complex length, muscle contractile tissue displacement, and modulation of EMG activity during acute whole-body vibration. *Muscle Nerve* **40**, 420–429.

Craik KJW (1947). Theory of the human operator in control systems. I. The operator as an engineering system. *Brit J Psychol Gen Sect* **38**, 56–61.

Craik KJW (1948). Theory of the human operator in control systems. II. Man as an element in a control system. *Br J Psychol Gen Sect* **38**, 142–148.

Evans CM, Fellows SJ, Rack PM, Ross HF & Walters DK (1983). Response of the normal human ankle joint to imposed sinusoidal movements. *J Physiol* **344**, 483–502.

Faisal AA, Selen LP & Wolpert DM (2008). Noise in the nervous system. *Nat Rev Neurosci* **9**, 292–303.

Gawthrop P, Loram I, Lakie M & Gollee H (2010). Intermittent control: A computational theory of human control. *Biol Cybern* (in press).

Gawthrop P & Wang L (2007). Intermittent model predictive control. *Proc Inst Mech Eng I* **221**, 1007–1018.

Gawthrop PJ (2009). Frequency-domain analysis of intermittent control. *Proc Inst Mech Eng I* **223**, 591–603.

Gawthrop PJ & Wang L (2006). Intermittent predictive control of an inverted pendulum. *Control Eng Pract* **14**, 1347–1356.

Gawthrop PJ & Wang L (2009). Event-driven intermittent control. *Int J Control* **82**, 2235–2248.

Gollee H, Hunt KJ & Wood DE (2004). New results in feedback control of unsupported standing in paraplegia. *IEEE Trans Neural Syst Rehabil Eng* **12**, 73–80.

Halliday DM, Rosenberg JR, Amjad AM, Breeze P, Conway BA & Farmer SF (1995). A framework for the analysis of mixed time series/point process data–theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Prog Biophys Mol Biol* **64**, 237–278.

Hanneton S, Berthoz A, Droulez J & Slotine JJE (1997). Does the brain use sliding variables for the control of movements? *Biol Cybern* **77**, 381–393.

Harris CM & Wolpert DM (1998). Signal-dependent noise determines motor planning. *Nature* **394**, 780–784.

Hinder MR & Milner TE (2003). The case for an internal dynamics model versus equilibrium point control in human movement. *J Physiol* **549**, 953–963.

Kiemel T, Elahi AJ & Jeka JJ (2008). Identification of the plant for upright stance in humans: multiple movement patterns from a single neural strategy. *J Neurophysiol* **100**, 3394–3406.

Kiemel T, Oie KS & Jeka JJ (2006). Slow dynamics of postural sway are in the feedback loop. *J Neurophysiol* **95**, 1410–1418.

Lakie M, Caplan N & Loram ID (2003). Human balancing of an inverted pendulum with a compliant linkage: neural control by anticipatory intermittent bias. *J Physiol* **551**, 357–370.

Lakie M & Loram ID (2006). Manually controlled human balancing using visual, vestibular and proprioceptive senses involves a common, low frequency neural process. *J Physiol* **577**, 403–416.

Lakie M & Robson LG (1988). Thixotropic changes in human muscle stiffness and the effects of fatigue. *Q J Exp Physiol* **73**, 487–500.

Loram ID, Gawthrop PJ & Lakie M (2006). The frequency of human, manual adjustments in balancing an inverted pendulum is constrained by intrinsic physiological factors. *J Physiol* **577**, 417–432.

Loram ID, Kelly S & Lakie M (2001). Human balancing of an inverted pendulum: is sway size controlled by ankle impedance? *J Physiol* **532**, 879–891.

Loram ID & Lakie M (2002). Human balancing of an inverted pendulum: position control by small, ballistic-like, throw and catch movements. *J Physiol* **540**, 1111–1124.

Loram ID, Lakie M & Gawthrop PJ (2009). Visual control of stable and unstable loads: what is the feedback delay and extent of linear time-invariant control? *J Physiol* **587**, 1343–1365.

Loram ID, Maganaris CN & Lakie M (2005*a*). Active, non-spring-like muscle movements in human postural sway: how might paradoxical changes in muscle length be produced? *J Physiol* **564**, 281–293.

Loram ID, Maganaris CN & Lakie M (2005*b*). Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius. *J Physiol* **564**, 295–311.

Loram ID, Maganaris CN & Lakie M (2007). The passive, human calf muscles in relation to standing: the short range stiffness lies in the contractile component. *J Physiol* **584**, 677–692.

Maurer C & Peterka RJ (2005). A new interpretation of spontaneous sway measures based on a simple model of human postural control. *J Neurophysiol* **93**, 189–200.

Mergner T, Maurer C & Peterka RJ (2002). Sensory contributions to the control of stance: a posture control model. *Adv Exp Med Biol* **508**, 147–152.

Miall RC, Weir DJ & Stein JF (1993). Intermittency in human manual tracking tasks. *J Mot Behav* **25**, 53–63.

Milton JG, Ohira T, Cabrera JL, Fraiser RM, Gyorffy JB, Ruiz FK, Strauss MA, Balch EC, Marin PJ & Alexander JL (2009). Balancing with vibration: a prelude for "drift and act" balance control. *PLoS One* **4**, e7427.

Navas F & Stark L (1968). Sampling or intermittency in hand control system dynamics. *Biophys J* **8**, 252–302.

Neilson PD & Neilson MD (2005). An overview of adaptive model theory: solving the problems of redundancy, resources, and nonlinear interactions in human movement control. *J Neural Eng* **2**, S279–312.

Neilson PD, Neilson MD & O'Dwyer NJ (1988*a*). Internal models and intermittency: a theoretical account of human tracking behavior. *Biol Cybern* **58**, 101–112.

Neilson PD, O'Dwyer NJ & Neilson MD (1988*b*). Stochastic prediction in pursuit tracking: an experimental test of adaptive model theory. *Biol Cybern* **58**, 113–122.

Pintelon R & Schoukens J (2001). *System Identification: A Frequency Domain Approach*. Institute of Electrical and Electronic Engineers, New York.

Poulton E (1974). *Tracking Skill and Manual Control*. Academic Press, New York.

Rack PM, Ross HF, Thilmann AF & Walters DK (1983). Reflex responses at the human ankle: the importance of tendon compliance. *J Physiol* **344**, 503–524.

Resulaj A, Kiani R, Wolpert DM & Shadlen MN (2009). Changes of mind in decision-making. *Nature* **461**, 263–266.

Ronco E, Arsan T & Gawthrop PJ (1999). Open-loop intermittent feedback control: Practical continuous-time GPC. *IEEE Proceedings-Control Theory and Applications* **146**, 426–434.

Slifkin AB, Vaillancourt DE & Newell KM (2000). Intermittency in the control of continuous force production. *J Neurophysiol* **84**, 1708.

Squeri V, Masia L, Casadio M, Morasso P & Vergaro E (2010). Force-field compensation in a manual tracking task. *PLoS One* **5**, e11189.

Vallbo AB & Wessberg J (1993). Organization of motor output in slow finger movements in man. *J Physiol* **469**, 673–691.

van der Kooij H & de Vlugt E (2007). Postural responses evoked by platform pertubations are dominated by continuous feedback. *J Neurophysiol* **98**, 730–743.

van der Kooij H & van der Helm FCT (2005). Observations from unperturbed closed loop systems cannot indicate causality. *J Physiol* **569**, 705.

Vince MA (1948). The intermittency of control movements and the psychological refractory period. *Brit J Psychol Gen Sect* **38**, 149–157.

Voss M, Ingram JN, Haggard P & Wolpert DM (2006). Sensorimotor attenuation by central motor command signals in the absence of movement. *Nat Neurosci* **9**, 26–27.

Voss M, Ingram JN, Wolpert DM & Haggard P (2008). Mere expectation to move causes attenuation of sensory signals. *PLoS One* **3**, e2866.

Wolpert DM, Ghahramani Z & Jordan MI (1995). An internal model for sensorimotor integration. *Science* **269**, 1880–1882.

Wolpert DM, Miall RC, Winter JL & Stein JF (1992). Evidence for an error deadzone in compensatory tracking. *J Motor Behav* **24**, 299–308.

Author contributions

These experiments were performed at the Institute for Biomedical Research into Human Movement and Health,

Manchester Metropolitan University. Each author contributed to the conception and design of the experiments, collection, analysis and interpretation of data, drafting of the article and revising it critically for important intellectual content. All authors approved the final version of the manuscript.

Acknowledgements