Proactive Selective Inhibition Targeted at the Neck Muscles: This Proximal Constraint Facilitates Learning and Regulates Global Control

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***Abstract*—While individual muscle function is known, the sensory and motor value of muscles within the whole-body sensorimotor network is complicated. Specifically, the relationship between neck muscle action and distal muscle synergies is unknown. This work demonstrates a causal relationship between regulation of the neck muscles and global motor control. Studying violinists performing unskilled and skilled manual tasks, we provided ultrasound feedback of the neck muscles with instruction to minimize neck muscle change during task performance and observed the indirect effect on whole-body movement. Analysis of ultrasound, kinematic, electromyographic and electrodermal recordings showed that proactive inhibition targeted at neck muscles had an indirect global effect reducing the cost of movement, reducing complex involuntary, task-irrelevant movement patterns and improving balance. This effect was distinct from the effect of gaze alignment which increased physiological cost and reduced laboratory-referenced movement. Neck muscle inhibition imposes a proximal constraint on the global motor plan, forcing a change in highly automated sensorimotor control. The proximal location ensures global influence. The criterion, inhibition of unnecessary action, ensures reduced cost while facilitating task-relevant variation. This mechanism regulates global motor function and facilitates reinforcement learning to change engrained, maladapted sensorimotor control associated with chronic pain, injury and performance limitation.**

***Index Terms*—Neck, rehabilitation, sensorimotor control.**

I. INTRODUCTION

THIS investigation arose from the practical problem of changing highly engrained sensorimotor control in skilled musicians. Motivation to change established sensorimotor control usually arises later in life. For example, individuals depending professionally upon skilled motor performance acquired through years of training may experience difficulties jeopardizing their livelihood. Deterioration of motor skill and problems of coordination, pain and injury can accumulate to chronic conditions in a variety of contexts. The nervous system uses immediate reward to drive reinforcement learning [1]. If departing from the established control pattern leaves one unable to function, professionally or otherwise, the path to re-learning is rewarded less than the current sensorimotor control. When complex patterns of control are involuntary and depended upon, the extent to which those patterns are flexible and the appropriate method to facilitate learning are open questions.

Our general hypothesis is that the segmental structure of the body provides a basis to the organization of motor output which can be exploited to facilitate sensorimotor learning. The planning of distal motor patterns may depend upon constraints applied at proximal locations within a kinematic chain. Adding a proximal constraint to the task goal should change the control of all distal segments. To test this hypothesis we chose a proximal node likely to show a strong effect on distal motor patterns. Almost all sensorimotor tasks (looking, upright balance, locomotion, reaching and grasping) require control of the head relative to the trunk. For reasons of proprioception, axial-appendicular and proximal-distal neuromuscular organization, the neck is likely to influence processes planning motor output. Using visual ultrasound feedback, participants targeted proactive inhibition at the neck muscles to alter neck muscle action during manual tasks. To achieve a desired goal, consistent with neck muscle inhibition, should require changes in the global motor plan forcing a change in highly automated sensorimotor control. Constraints applied proximally may interfere with or facilitate the task. We test the idea that minimization of proximal action unnecessary to the task, may make the task easier. We state three specific hypotheses.

H1: Neck muscle movement can be regulated voluntarily while maintaining task performance.
H2: There is a causal relationship between voluntary regulation of neck muscles and global control of movement.
H3: Proactive-selective inhibition targeted at the neck muscles reduces the global cost of movement.

Selective inhibition is the ability to prevent muscular action incongruent with the task goal, while concurrently allowing functionally relevant muscle action [2], [3]. While some

Manuscript received April 30, 2016; revised September 24, 2016; accepted December 7, 2016. Date of publication December 21, 2016; date of current version April 11, 2017.

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This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the authors. This downloadable zip file includes the document “Supplementary material on use of ultrasound for biofeedback and analysis Final Version.pdf” and a folder “Supplementary Material Graphic and Media Files” containing multimedia material referenced in the document “Supplementary Material.pdf.” The document includes the following sections Supplementary methods on this use of ultrasound for biofeedback and analysis, Supplementary results, and Supplementary Discussion.

Digital Object Identifier 10.1109/TNSRE.2016.2641024

selection occurs at the levels of spinal cord and brain stem, the most powerful mechanisms for selection and modification of selection (reinforcement learning) are centralized and occur through the slow frontal-striatal loops [2]–[4]). Proactive refers to the use of environmental information to prepare the forthcoming inhibitory action [3].

In support of our hypotheses, there are known differences in innervation and control of axial and appendicular muscles [5]. Also there is evidence linking head orientation and head control instruction to global postural control [6], [7]. In some studies, activation of muscles proceeds sequentially from proximal reference or stabilizing segments to distal segments. During reaching movements activation can proceed temporally from the head-trunk to end of the arm [8]–[10]. More generally, even when global activation is more synchronous, activation of the proximal neck–trunk–legs anticipates and is typically organized around movement of the distal end segment (eye, head, finger, foot) that is defined by the task goal [11]. This phenomenon is known as anticipatory postural adjustment, but the key principle is that the nervous system organizes control of the whole body in relation to the task goal. Combined with the task goal, the current configuration of the body provides input to the construction of global motor output [12], [13]. The effect of any constraints applied proximally accumulates along the kinematic chain from the reference, stabilizing segment, to the distal end segment. Hence, the planning of global motor patterns may depend upon constraints applied at the neck. Understanding this organization may help to promote regulation of global control and facilitate learning.

Contrary to our hypotheses there is evidence that an internal focus of attention and conscious control of movement both increase cost and impair task performance [14]–[16]. Generally, attention to the movement of one's own body ("internal focus of attention") and feedback about the actual execution of a movement ("knowledge of performance") is considered to be less beneficial than attention to the effect of one's movements on the environment ("external focus of attention") and feedback about the extent to which a movement accomplished the intended goal ("knowledge of results") [14]–[16]. Attention to secondary goals unrelated to the main task goal is at best distracting, diverting resources from accomplishment of the main goal and at worst detrimental, introducing conflicting activity. An internal focus of attention is thought to encourage conscious control of movement, which is argued to constrain or inhibit detrimentally automatic control mechanisms (the "constrained action hypothesis"), whereas an external focus is considered to promote, a more automatic and more efficient mode of control by utilizing unconscious, fast, and reflexive control processes [15], [17]. Good control requires close regulation of the distal end goal while allowing higher variability of proximal elements [18]. Conflict between focus of attention theory and our results is considered in discussion.

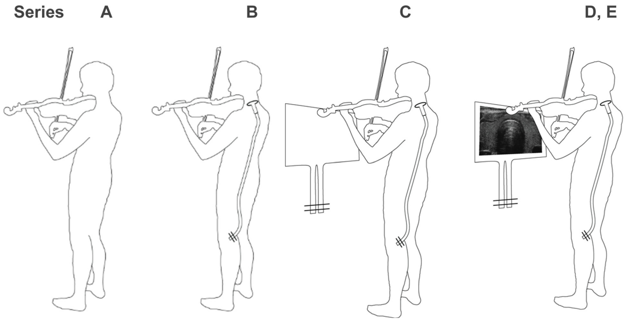

Fig. 1. **Experimental Design: Discriminating effect of voluntary inhibitory neck muscle regulation from gaze alignment**. Tasks were carried out in five experimental conditions designed to separate the effects of gaze alignment and US neck feedback from the effects of wearing the US probe and familiarization with the US information. Series A: Normal task performance with no US. Series B: Using the laboratory violin with an US probe attached to the participant's neck. Series C: Aligning the gaze. Series D: US familiarization. Series E: Using US mediated neck feedback.

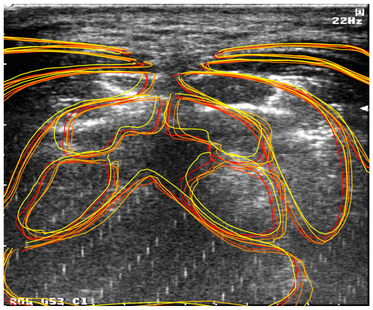

Fig. 2. **Transverse, laterally inverted US view of dorsal neck** at vertebral level C3-C4 as background image (first frame). Bilateral segmentation after the experiment, overlaid showing five layers of muscles (*trapezius*, *splenius*, *spinalis capitis*, *spinalis cervicis*, intrinsics) at 1 s intervals (red through orange to yellow, 0, 1, 2, 3, and 4 s)

It is unclear whether, subject to the constraints of performing designated tasks, the neck muscles are amenable to voluntary regulation. Ultrasound (US) feedback of the neck muscles during task performance provides a method that may enable us to directly alter neck muscle behavior. Using a dorsal cervical location with transverse probe orientation, US provides a bilateral view of five layers of muscles (Figs. 1 and 2). Visible muscle movement includes active contraction and changes caused passively by action of other muscles. This study uses ultrasound to provide feedback of the neck muscles with instruction to reduce any unnecessary change of the neck muscles during task performance (referred to as "neck regulation"), and reports observation of the indirect effect on whole body movement and muscle activation patterns.

Since US feedback of the neck muscles is given visually, the experiment required control conditions to isolate the effect of visually aligning the gaze to an external target, from that of using proactive, selective inhibition to regulate neck muscle behavior. Hence, in addition to normal task and neck regulation conditions, we used a condition in which participants aligned their gaze to a blank US monitor. The difference between these latter conditions reveals the exclusive effect of regulating the neck muscles during task performance. Further conditions controlled for the effect of wearing the US probe and familiarization with the visual US information.

To assess the direct effect on the neck muscles we used differentiated, bilateral ultrasound analysis of neck muscle movement within five dorsal layers. To assess the indirect, uninstructed effects we measured whole body movement, muscle activity and skin conductance. Fig. 3 shows our hypothesis testing flowchart.

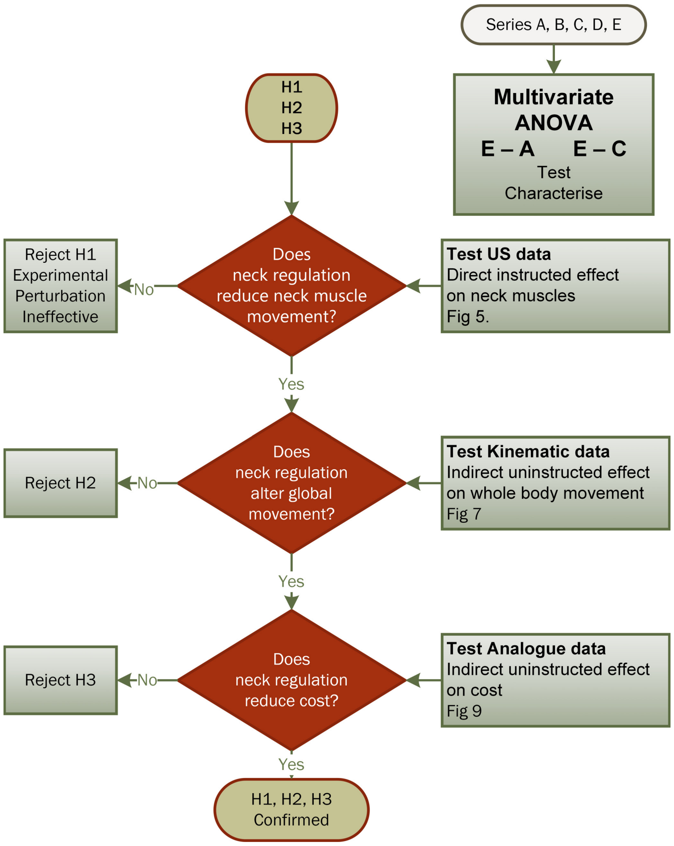

Fig. 3. **Method**. Using multivariate analysis, we test for significant effects of visually-mediated neck regulation (E v. A) and neck regulation distinct from gaze alignment to the monitor (E v. C). We test **H1**, the direct instructed effect of voluntary regulation on neck muscles using US data, **H2**, the indirect, uninstructed effect on whole body movement using Kinematic data and **H3**, the indirect effect on psychophysiological cost using Analogue data (EMG, skin conductance). We characterize **what** changes occur using univariate analysis, and **when** those changes occur using 1-D statistical parametric mapping of univariate time series (Fig. 6).

II. METHODS

A. Ethical Approval and Participants

These experiments, approved by the Faculty of Science and Engineering Research Ethics Committee, Manchester Metropolitan University (MMU), conformed to the standards set by the latest revision of the Declaration of Helsinki. Participants gave written, informed consent to these experiments, performed at the Cognitive Motor Function laboratory, MMU. Of the 21 players (16 violin, 5 viola) (age 19–74, 47 ± 14.7, range, mean ± SD; 12 female) who participated in the experiment, 10 were professionals, eight were amateurs, and three were students at a local music college.

B. Procedure

Following preparation for motion analysis and EMG recording, participants were given an extended period of familiarization playing their own violin and an instrumented laboratory violin. Participants used their own shoulder rest and bow. Four viola players chose to use their own instrument for all trials. The fifth played the laboratory violin. All subsequent references to "violin" include both violin and viola.

After familiarization, participants conducted a sequence of tasks intended to sample a range of manual activities that progressed from relatively non-specific unskilled actions through characterization of the configurations sustained in playing the violin. Participants performed these tasks on instruction, starting from and returning to, a neutral position in which their arms were relaxed at their side. The playing position was always maintained for more than 5 s.

Task 1: *Raising the arms*(without the violin): "bring both arms up to a playing position".
Task 2: *Raising the violin*: "bring the violin to the normal sustained playing position"
Task 3: *Raising the violin and bow as if to play*: "bring the violin and bow to the normal playing position as if to play".
Task 4: *Playing a scale*: "bring the violin and bow to the normal playing position and play the three-octave scale".
Task 5: *Playing a study*: "raise the violin and bow, and play part of the second study by Rodolphe Kreutzer".
Task 6: *Playing own piece*: "raise the violin and bow and play your chosen piece of music"

This sequence of tasks was undertaken in each of five series (below) aimed at testing the effects of gaze alignment (C) and neck regulation (E) on normal playing, with the necessary control series (A, B, C, and D) in place (Fig. 1). Series D and E had irreversible educational effects, undermining a random order design, so this order A-E was constant for all participants.

Series A: *Normal task performance with no intervention*. To determine participants' normal movements, using their own instrument, they were asked to perform the tasks as normally and as naturally as possible.
Series B: *Using the laboratory violin with an US probe attached to the participant's neck*. To test the effect of a change of instrument and the addition of an US probe taped to their neck, all tasks were repeated "wearing" the US probe and using the laboratory violin.
Series C: *Aligning the gaze*. To test the effect of aligning the gaze (and thus keeping the head relatively still), participants were asked to repeat all tasks as in Series B, but looking at the blank US monitor.
Series D: *Using US for movement - visual familiarization*. To test the effect of observing and formulating the association between task movements and changes in US image, participants were asked to repeat all tasks as in Series C while observing the live US view of their neck muscles. Following each task, participants were asked to describe all observed changes in US image and specify when in the task those changes occurred.
Series E: *US mediated inhibitory neck regulation*. To test the indirect effect of minimizing change in neck muscle movement whilst performing, participants were asked to repeat all Series D tasks, and attempt to minimize change in the US image while they performed the tasks.

We encourage the reader to access our supplementary material on this use of ultrasound for biofeedback and analysis including example videos (Supplementary Methods).

C. Apparatus and Measurements

A 10-camera motion analysis system (VICON, Oxford Metrics) and whole body marker set was used to track 18 segments (head, neck, thorax, pelvis, thighs, shanks, feet, clavicles, upper arms, forearms, hand. Having shaved and cleaned the skin, 14 surface (wireless) EMG electrodes (Trigno, Delsys) were placed bilaterally to record data from upper and lower *trapezius*, *tibialis anterior*, *vastus lateralis* and *medialis*, *gastrocnemius* and *semimembranosus* muscles. Galvanic skin conductance (GSC) was recorded via a custom-made wireless device [19]. Adhesive gel electrodes (Cardiacare, Herongate) were placed on the palmar aspect of the second and fourth finger of the right hand for differential recording. A custom-built, wireless strain gauge device measured compression force applied to the standard chinrest of the laboratory violin. For Series B to E, a T-shaped US probe (linear, 7.5 MHz, 50 mm field of view Aloka ProSound-5000), was attached to the dorsal neck of each participant at the level of C4 using micropore tape (Fig. 1), to provide a transverse view of five muscular layers (*trapezius*, *splenius*, *spinalis capitis*, *spinalis cervicis*, *rotatores / multifidus* (Fig. 2). US, kinematic and analogue data were synchronously sampled at 25 Hz, 100 Hz, and 1000 Hz, respectively. US quantities measure neck muscle movement (H1). Kinematic quantities measure whole body movement (H2). Analogue quantities (EMG, skin conductance, chinrest force) measure physiological cost and effort (H3).

D. Processing of US, Kinematic and Analogue Data

US video sequences were subjected to two stages of analysis—segmentation of muscles and tracking of muscle shape (Fig 2 and Supplementary Material). Within the transverse plane, left and right muscles from five layers (*trapezius*, *splenius*, *spinalis capitis*, *spinalis cervicis*, intrinsics (*multifidus*, *rotatores*) were automatically segmented at seven key frames (2 s intervals). This method, reported elsewhere, fits a generalized neck segmentation model, derived from an independent MRI-US dataset of 24 participants in the normal upright standing posture [20]. To capture muscle movement not represented by the standing posture, points around the boundary of each segment were tracked automatically forwards and backwards from each key-frame using a KLT tracker [21]. For each segmented muscle, for each frame, the median tracked boundary points were used to calculate the centroid location (x, y), segment area, segment rotation, centroid cumulative absolute movement and cumulative expansion. These six segmental measures capture all aspects of the muscle movement in a form that has a clear geometric meaning. US gives a 60 parameter state (10 muscles x 6 measures) of neck muscle movement. Due to technical issues in data collection, three participants were excluded from analysis giving an US dataset of 18 participants.

Using *Visual 3D* (*C-Motion*), an eighteen-segment, kinematic model was fitted to the marker data using "six-degree of freedom" inverse kinematics. From this model, seventeen model-based joint-rotations (ankles, knees, hips, thoraco-pelvic, sterno-clavicular, shoulders, elbows, wrists, neck (C7) and atlanto-occipital (AO)), each with three degrees of freedom (extension, adduction and axial rotation), were calculated, to give a 51 parameter state (17 joints x 3 dof) of whole body movement. In lab coordinates, we also calculated the whole body center of mass location (CoM) and the total angular momentum of all segments around the CoM (Visual3D function *model_angular_momentum*). All 21 participants were included in this analysis.

EMG data were high-pass-filtered (10 Hz) to remove offset, rectified and then low pass-filtered with a cut-off at 5 Hz. For each participant, low-pass-filtered EMG data, violin strain gauge and skin conductance were normalized to a robust estimate of the maximal value (90th percentile) from all their trials. For muscle EMG we calculated an additional measure, the accumulated positive change (*cEMG*) where

$$cEMG_n = \sum_{i=1}^{n} if \begin{cases} \Delta EMG_i > 0 & \Delta EMG_i \\ otherwise & 0 \end{cases}$$

This measure counts all prior increments irrespective of when they occur. Intermittent bursts in activity occurring at different prior times are given equal weight at the instant of comparison rather than being diluted by a low probability of occurrence at any particular instant. Violin strain gauge, EMG and skin conductance data were collected successfully for 12, 14, and 19 participants, respectively. Analogue quantities (14 muscles ×2 measures, skin conductance, strain gauge) provide maximally a 30 parameter state of physiological cost. For each trial, an "arm-raising event" was defined when the left finger marker first raised 20 cm above the origin of the pelvic segment (time zero, Fig 4). For each dataset (US, kinematic, analogue) we calculate the change between initial neutral standing state (PRE), and sustained playing position (RAISED). These states were calculated using mean values from the intervals -2 to -1 s and 1 to 8 s (c.f. Fig 4). The change in state (RAISED minus PRE) represents neck muscle movement, whole body movement and physiological cost for US, kinematic and analogue datasets. We subject the change in state to univariate and multivariate statistical analysis.

E. Statistical Analysis

Univariate analysis: For each dataset, all parameters (RAISED minus PRE) were tested individually using repeated measures ANOVA with Greenhouse-Geisser adjustment for deviations from compound symmetry. Series (five levels A–E) and Task (six levels 1–6) were within subject factors and Participant was a random factor. Panel D in Figs. 5, 7, and 9 shows the quantities most significant for Series. This panel shows common patterns between series for all variables. The reader is encouraged to focus on those patterns rather than individual parameters.

Multivariate analysis: US, Kinematic and Analogue states (RAISED minus PRE) were analyzed in separate datasets

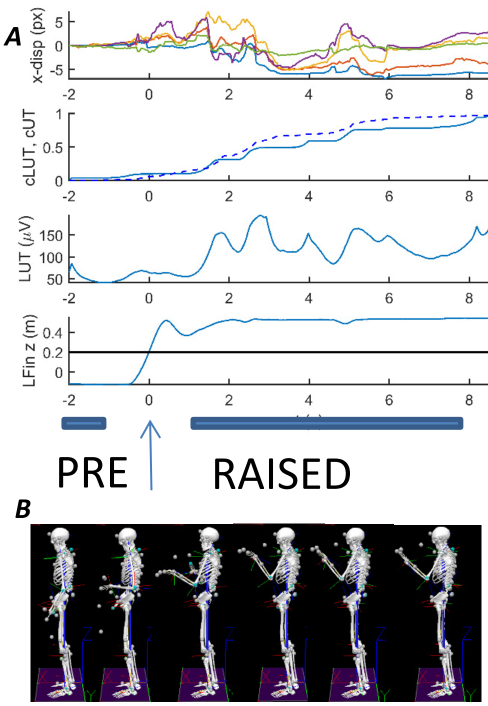

Fig. 4. **Representative task and measurements** Starting from neutral with the arms hanging vertically, the participant raised the violin using the left arm. Raising the left hand 20 cm above the pelvis defined an event and time 0 s.

A. Rows in descending order (i) Centroid x-displacement in transverse US image of left neck muscle segments (blue- *trapezius*, red- *splenius*, yellow- *spinalis capitis*, magenta- *spinalis cervicis*, green-intrinsics), (ii) left upper trapezius (LUT) accumulated positive change *EMG* (solid) and accumulated absolute movement US (dashed) (iii) surface EMG from left upper *trapezius*, (iv) vertical height of third metacarpal marker relative to origin of pelvis segment (LFin wrt Pelvis z). For all quantities the mean value during times -2 to -1 s is recorded as PRE, and the mean value during time 1 to 8 s (or when LFin wrt Pelvis z less than 0.2 s) is recorded as RAISED. The change, RAISED minus PRE, is recorded for statistical analysis. ***B*** Kinematic analysis fitting 18 segment "6 DoF" kinematic model to Vicon marker data at times (-1, 0, 1, 2, 3, 4 s).

using respectively 60, 51, 29 (strain gauge excluded) parameters and 18, 21, 14 participants.

We calculated *Mahalanobis* distance to quantify distance between Series in canonical units of covariance. *Mahalanobis* distance is a scale-invariant, multidimensional measure of separation between points in units of variance. This distance also shows effect size. For Panel A in Figs. 5, 7, and 9 the horizontal link joining Series or clusters of Series shows the mean *Mahalanobis* distance between centers.

To reduce the multiple variables to orthogonal univariate quantities which maximize the separation between Series, we calculated and ranked in descending order the four eigenvectors of the matrix (*between series sum of squares / within series sum of square*) [22]. Each eigenvector, represents a distinct pattern of variables.

For US, Kinematic and Analogue quantities respectively, these eigenvectors provide patterns of neck muscle movement, whole body movement, and muscle cost discriminating Series A-E. To show these patterns, panels B/C in Figs. 5, 7, and 9 show the trial scores from the first two of these linear, canonical, discriminant functions (DF1, DF2). These scores were tested for significant difference between series using univariate repeated measures ANOVA, as above, with Tukey-Kramer *post hoc* pairwise comparisons. These trial scores were also tested for correlation with all quantities to produce the "structure matrix″ [22]. Within Matlab 2015b,

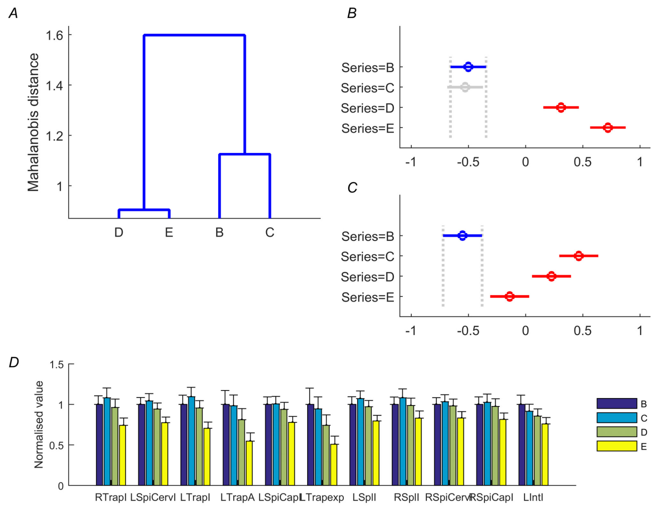

Fig. 5. **Direct instructed effect of neck regulation on neck muscles (US)**

A: *Mahalanobis* distance between series. Neck regulation had a greater effect on neck muscle movement than gaze alignment. Relative to normal task performance (Series B), neck regulation (Series E) had a *Mahalanobis* distance of 1.8., whereas gaze alignment (Series C) had a distance of 1.1. Distance Series E from C was 0.9.

B, C: Neck regulation and gaze alignment were associated with distinct patterns of effect on neck muscle movement. Horizontal axis shows trial scores ±95% confidence intervals from the first two orthogonal canonical discriminant functions (DF1, DF2) in units of standard deviation. Red indicates series which differ significantly different from Series B (blue).

B. DF1 accounting for 54% of the variance between series, represented a pattern most strongly associated with neck regulation (Series E), and unassociated with gaze alignment (Series C). DF1 showed a significant difference between series (repeated measures ANOVA, p <0.0001). Tukey-Kramer pairwise comparison showed neck regulation (Series E) and US familiarization trials (Series D) were significantly different from normal performance (Series B), whereas the gaze alignment trials (Series C) were not. Correlation of all US quantities with DF1 showed **DF1 represents a general reduction in muscle movement**.

C. DF2 accounted for 28% of the variance between series, and represented an orthogonal pattern most strongly associated with gaze alignment, but also partially common to US familiarization and neck regulation. DF2 showed a significant difference between series (p <0.0001), with Series C, D and E all significantly different from Series B. Correlation of DF2 with all US quantities showed
DF2 represented mainly an increase in muscle movement.

D: The most significant univariate effects of Series on neck muscles (US) in descending order of significance rightwards to alpha$<$0.005. Bars show means ±95% confidence intervals, grouped by series. Quantity labels are Trap-*trapezius*; SpiCerv-*spinalis cervicis*; SpiCap-*spinalis capitis*; Spl-*splenius*; Int-*intrinsics*; I-cumulative absolute movement; A-area; exp-cumulative expansion;

Univariate analysis confirms, for individual quantities, the superposition of monotonic (DF1) and bitonic (DF2) patterns through Series A to E. Visual feedback with instruction to minimize unnecessary neck muscle movement (Series E, and D partially), resulted in a consistent systematic reduction in muscle movement generally for all muscles and most significantly for the left neck muscles. Gaze alignment (Series C), showed a tendency (absolute, and relative to the monotonic pattern of DF1) to increase muscle movement. At p < 0.05, no quantities showed significant interaction between factors Series and Task.

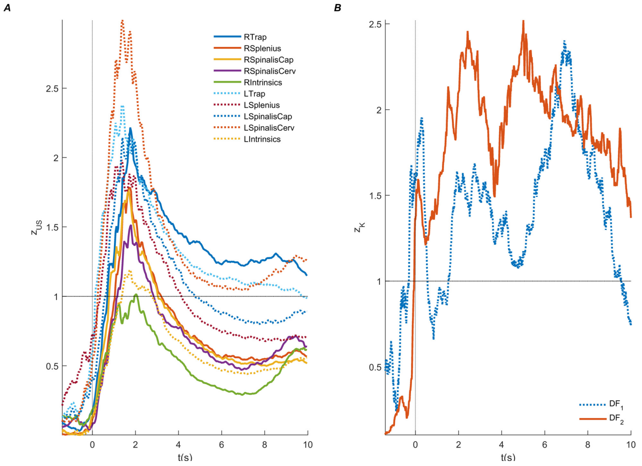

Fig. 6AB. **Evolution through time of effect of neck regulation** A-B temporal evolution of effect of Series (mainly neck regulation): z is SPM (F) relative to threshold of significance for quantity tested.

A: Accumulated absolute US movement of neck muscles tested. Shows stronger, earlier effect on appropriate muscles for the movement sequence left neck flexion/head turn followed by right arm action.
B: Kinematic discriminant function scores (DF_1, DF_2). Shows exclusive effect of neck regulation on global pattern of movement (E-C), (DF_2) is simultaneous with and sustained throughout the task. Shows effect common to all series requiring gaze alignment (C, D, E) (DF_1) anticipates task and is less sustained.

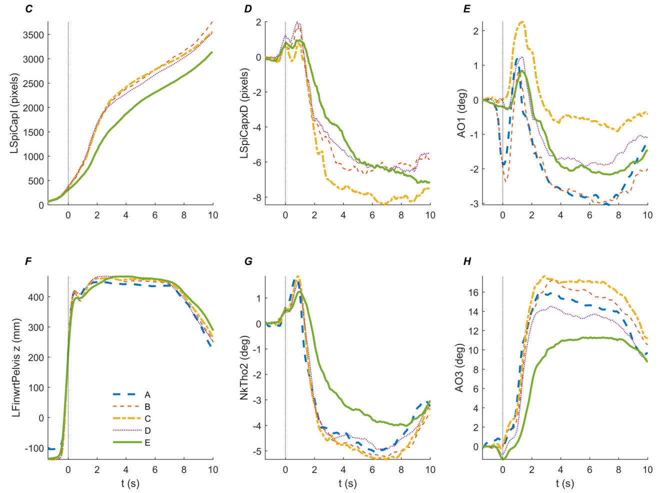

Fig. 6CDEFH. Panels C-R show mean values for each series: Time zero is when the left finger first rises 20 cm above the pelvis origin. Axes 1, 2, 3 are right, forwards, up.

Head Control: C: Left *spinalis capitis* accumulated US movement; shows an effect of neck regulation distinct to Series E and not arising naturally during the sequence of familiarization trials, and 4 × 6 trials during Series A to D.
D: *Left spinalis capitis* US x-displacement; neck regulation (Series E) reduces transient muscle movement whereas gaze alignment (Series C) adds movement.
E: Atlanto-occipital extension; all Series C-E eliminated the initial head flexion. Neck regulation delayed and reduced head movement whereas gaze alignment (Series C) increased head extension and then preserved initial joint angle, consistent with regulation of position to a predetermined value.
F: Vertical left hand movement; shows consistency in space and time of raising and holding the violin during all series.
G: Neck right lateral flexion relative to thorax; neck regulation is distinct from all preceding series in delaying and reducing neck movement resulting in reduced lateral flexion of the head onto the violin.
H: Atlanto-occipital axial rotation to left; neck regulation, distinct from all series delays and reduces whereas gaze alignment increases turning the head towards the violin.
We interpret Series E results as consistent with ongoing inhibitory neck regulation whereas Series C is consistent with focus to the US monitor.

functions “ *manova1* ”, and “ *fitrm* ” were used respectively to calculate the canonical discriminant functions and conduct the repeated measures analysis.

Time series analysis: to assess the timing of significant difference between Series A-E, selected univariate time series were tested using 1-D statistical parametric mapping implemented by the open-source toolbox SPM1D (v.M0.1, www.spm1d.org, “anova1rm”) [23]. SPM1D calculates the chosen statistic at each temporal sample and calculates a threshold of significance appropriate for the partial independence of measurements repeated through time. SPM1D avoids the false positives of multiple scalar tests and avoids the false negatives of scalar tests with Bonferroni correction. Fig. 6A-B, Fig. 6O-Q shows the temporal evolution of the F-statistic (repeated measures anova, effect of series) relative to the threshold of significance for the quantity tested. To determine when and where the direct effect of neck regulation occurs, we apply SPM1D to the temporal evolution of the accumulated absolute movement of the neck muscles from US data (Fig. 6A). To determine when the indirect effect of neck regulation on global movement occurs we apply SPM1D to the evolution through time of the trial scores of the first two kinematic discriminant functions (Fig. 6B). These trial scores were calculated at every sample, using the kinematic eigenvectors (DF1, DF2). All time series presented in Fig. 6 show significant effect of Series at $p < 0.05$.

III. Results

For all Series A-E, participants completed all tasks successfully, all holding the violin conventionally on the left side between shoulder and chin. During data collection playing performance was perceived by the experimenters as indistinguishable between conditions. Subsequent scoring of the randomized recordings (Tasks 4-6) for playing quality by two experienced assessors each showed no significant effect of Series ($p = 0.44$, $p = 0.81$ resp). Both hands showed no significant change in speed or timing during raising to the playing position though there was an altered, smoother trajectory to final positioning during series E (Figs. 3–6 Supplementary Material (SM)). During Series E, sound was produced later at 4.7 s compared with 3.3, 4.0, 3.6, 3.9 s mean times for Series A-D, respectively (Fig. 4. SM).

Representative trial. Starting from the neutral position, Fig. 4 shows a participant, raising the violin with the left hand (approx. -0.5 to 1 s), placing and holding the violin under the chin (approx. 1–2 s) (Series B, Task 2). Execution is reflected by clear preceding and accompanying changes in the neck muscles, most salient in the left *spinalis capitis* and *cervicis*. US and EMG analysis of the left upper *trapezius* both show the cumulative step-like change in muscle movement and activity.

Group results: All following results report group analysis of the entire data set. Using the flowchart of Fig. 3 the change

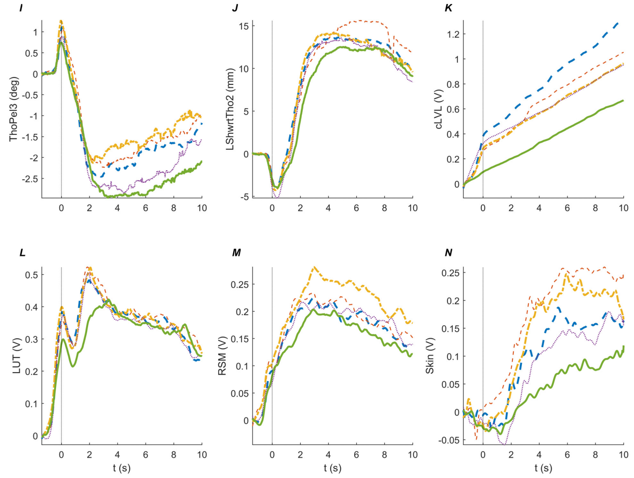

Fig. 6JKLMN. **Localised cost.**
I: Thorax axial thoraco-pelvic rotation. Positive is clockwise around vertical axis. Neck regulation increases rightwards rotation of thorax towards sustained playing position at 2s. c.f. Fig. 6Q.
J: L Shoulder anterior displacement relative to thorax; neck regulation, distinct from all preceding Series reduced shoulder protraction toward the violin shoulder rest. N.B. shoulder protraction requires action of multiple muscles, involves increased effort, increases grip force on the violin and is associated with chronic injury in violinists.
K: cumulative positive change in left *vastus lateralis* EMG; shows the distinct effect of neck regulation (Series E), unobserved in their series, reducing anticipatory activation in the leg.
L: Left upper *trapezius* EMG; shows a reduction, unique to neck regulation, in activity associated with raising the left arm. The action of this muscle is retractive elevation of the scapula.
M: Right *semimembranosus* EMG; shows an effect of neck regulation reducing activity in the right posterior upper leg associated with supporting the violin on the left side of the body.
N: Skin Conductance: Neck regulation reduced the delayed rise in skin conductance associated with task performance. Skin conductance measures solely sympathetic arousal.

RAISED minus PRE was tested systematically. The main text reports the key findings. Figure captions report detailed results.

A. The direct, instructed effect of neck regulation on neck muscles

Analysis of all US neck muscle quantities (Fig. 5) showed that neck regulation using visual feedback was effective in reducing neck muscle movement and produced a pattern of effect distinct from the effect of alignment of gaze. Neck regulation had a greater effect on neck muscle movement than gaze alignment (Fig. 5A). Neck regulation was associated with a general reduction in neck muscle movement (Fig. 5B) whereas gaze alignment was associated with a different pattern which included increases in neck muscle movement (Fig. 5C). For individual parameters, Fig. 5D shows these distinct patterns across Series. Following the flow chart of Fig. 3, these results confirm hypothesis H1, that neck muscle movement can be regulated voluntarily while maintaining task performance.

Fig. 6 A shows how the effect of neck regulation occurred early during raising the left arm, was strongest, and earlier on the left neck muscles, particularly left *spinalis cervicis* and subsequently strongest on right *trapezius*. Fig. 6C-D illustrates an early, distinct effect of neck regulation (Serie E) in reducing muscle movement and the increased muscle movement observed during gaze alignment (Series C).

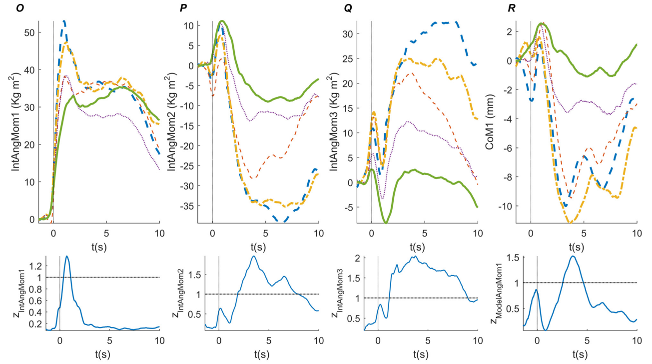

Fig. 6OPQR. **Global balance and unnecessary cost:** Panels associate neck inhibition, with regulation of global balance and global rotation during the disturbing effect of the tasks. O-Q show time integrated angular momentum which equates to rotation of whole-body mass around the global centre of mass (CoM). Gradient = instantaneous global angular momentum around CoM. Positive lab axes 1, 2, 3 are right, forwards, up.

O: Positive is clockwise rotation (CR) around right horizontal axis. Shows neck regulation minimizes unnecessary over generation and cancellation of upwards momentum when raising hands-violin to playing position (0–2 s).
P: Positive is CR around forwards horizontal axis. Shows neck regulation minimizes unnecessary, costly, global leftwards frontal rotation around CoM, sustained in playing position (2–8 s).
Q: Positive is CR around vertical axis. Neck regulation minimizes leftwards global axial twisting sustained in playing position (1–9 s).
R: Center of mass location, whole body. Positive=right. Neck regulation minimizes left movement of CoM during playing position (3–5 s).
Four markers (Chinrest, Fingerboard, ScrollThumb, ScrollFinger) tracked the violin segment during Series B-E. N.B. Series A does not include Violin. Bottom row: SPM(F) scores relative to threshold.

B. The indirect uninstructed effect of neck regulation on whole body movement

Considering all rotation axes from seventeen joints, Fig. 7 shows that neck regulation produced uninstructed changes in movement throughout the body, most significantly in the head and neck but also in the arms, lower trunk and legs. Neck regulation had a greater effect on whole body joint rotations than Gaze Alignment (Fig. 7A). There was a substantial pattern of effect common to both conditions (Fig. 7B) and also a substantial pattern discriminating neck regulation from gaze alignment (C-E), (Fig. 7C). These patterns can be seen in the effect of Series on joint rotations throughout the body (Fig. 7D). The effect of neck regulation distinct from the effect of gaze alignment confirms hypothesis H2 of a causal relationship between voluntary regulation of neck muscles and global control of movement (Fig. 3).

Complete representation of the effects of gaze alignment and neck regulation on the whole body movement requires combining the effects of all joint rotations, not just those rotations which show significant univariate differences (Fig. 8). We report a summary combining the structure matrix of correlations of all joint rotations and laboratory referenced segment angles with DF1 and DF2, the time series of Fig. 6, and also provide the visualization of Fig. 8. Compared with normal task movement, gaze alignment common to contrasts (A-C) and (A-E) reduced *atlanto-occipital* (AO) and neck flexion, and laboratory-referenced flexion of the head and neck and reduced laboratory-referenced axial rotation of the

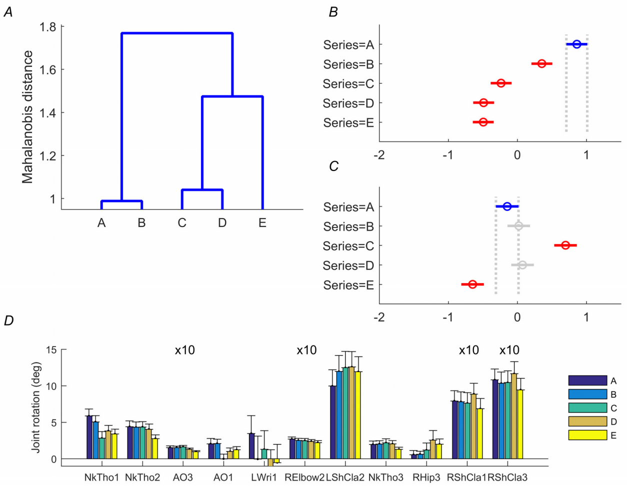

Fig. 7. **Indirect, uninstructed effect of neck muscle regulation on whole body movement.**

A: *Mahalanobis* distance between series. Neck regulation had a greater effect on Movement than Gaze Alignment. Relative to normal task performance (Series A, B), neck regulation (Series E) had a mean *Mahalanobis*distance of 1.9, whereas gaze alignment had a mean distance of 1.7 (Fig. 6A). Distance of Series E from C was also 1.9.

In common with the US analysis, neck regulation and gaze alignment were associated with distinct patterns of effect on global joint rotation (RAISED minus PRE).

B, C: Trial scores of first two discriminant functions (DF1, DF2 resp.). Red indicates significant different from Series A (blue).
DF1 (46% of variance), represented a pattern common to all series requiring gaze towards the US machine (Series C, D, E). DF1 showed a significant difference between series ($p < 0.0001$) and significant difference of Series C, D and E from A.
DF2 (30% variance) represented a pattern discriminating Neck regulation (Series E) from Gaze Alignment (Series C). DF2 showed significant difference between series ($p < 0.0001$), with only Series E and C significantly different from Series A.
D. The superposition of patterns of DF1 and DF2 is seen for individual quantities. There were significant univariate effects of Neck regulation (Series E-A) on neck head, arm and leg movements. Significant Series-Task interaction was confined to thoraco-pelvic and right ankle joints. Bars show means ±95% confidence intervals, for the most significant univariate effects of series on joint rotation in descending order of significance to alpha$<$ 0.005. NkTho-Neck relative to thorax; AO-Head relative to neck (Atlanto-occipital); Wri-Hand relative to forearm, ShCla-Upper arm relative to clavicle; ThoPe-Thorax relative to pelvis. Rotation axes 1 right (extension), 2 forwards (lateral), 3 upwards (axial).

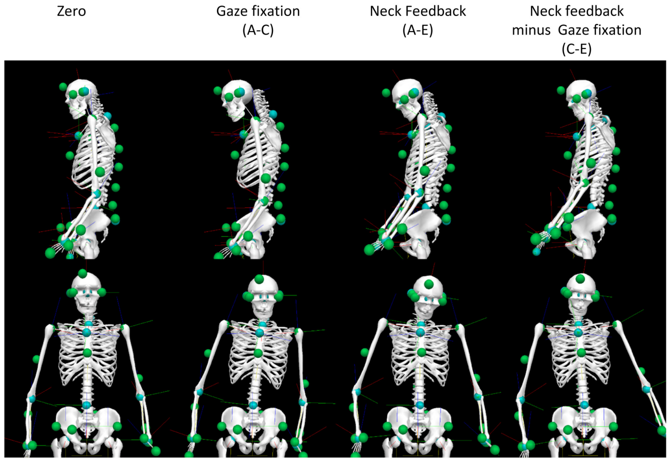

Fig. 8. **Task-independent movement eliminated by gaze alignment and neck regulation**.
For each series the mean joint rotations were computed (RAISED minus PRE). Cols 1–3 show the difference in mean joint rotation between series (magnification x5) added to the mean pre task kinematic location (PRE) of all trials from all participants in Series A.
Col 1 (**zero**) shows the null case of zero difference (A-A) and thus shows the mean pre task kinematic location (PRE) of all trials from all participants in Series A.
Col 2 (**Gaze alignment**) shows the difference (A-C) and thus shows the joint rotation present normally (Series A) and removed by gaze alignment (Series C).
Col 3 (**Neck regulation**) shows the difference (A-E) and thus shows the joint rotation present normally (Series A and removed by neck feedback (Series E).
Col 4 (**Neck regulation minus Gaze alignment**) shows the difference (C-E) and thus shows the joint rotation present during gaze alignment (Series C) and removed by neck feedback (Series E).

whole body above the right hip (Fig. 8 cols 2, 3). Fig. 8 shows movement removed by neck regulation which is not removed by gaze alignment, contrast (C-E). Neck regulation alone reduced axial, lateral and extensor rotations of the head and neck, downwards compression of the head relative to the thorax, forward movement of the shoulders, particularly the left shoulder and abduction of the arms relative to the thorax, and increased axial rotation of the thorax relative to the pelvis. In summary, gaze alignment removed movement of the head and trunk relative to the laboratory frame of reference, whereas neck regulation *per se* removed displacement of body parts relative to the trunk while redistributing axial rotation.

C. The indirect uninstructed effect of neck regulation on analogue quantities

The analogue quantities (fourteen muscle activities, skin conductance, violin strain gauge) each provide a measure of the physiological cost of the task. For trials with recorded analogue quantities, significant analogue correlations with Movement DF1 (Fig. 7B) were exclusively positive, meaning that the effect common to gaze alignment (C-A) and neck regulation (E-A) was a reduction in muscle activities, skin conductance and chin rest compression. Furthermore, all significant analogue correlations with DF2 (Fig. 7C) were exclusively positive, meaning that pure neck regulation was associated with reductions whereas gaze alignment was associated with increases in all muscle activities, skin conductance and compressive force on the chinrest.

Fig. 9 reports independent analysis of combined analogue quantities. Neck regulation had the greatest effect on cost and had a greater effect than gaze alignment (Fig. 9A). Neck regulation was associated (DF1) with decreased cost (Fig. 9B, and D). Gaze alignment was associated with a different pattern (DF2) of increased cost (Fig. 9C and D). Following Fig. 3, these results confirm hypothesis H3, that proactive-selective inhibition targeted at the neck muscles indirectly reduces the global cost of movement.

Fig. 6 details the timing and nature of the effect of neck regulation on head control (Fig. 6C-H), localized cost within the lower back, upper limb and legs (Fig. 6I-N) and global balance (Figs. 6 O-R). Neck regulation (Series E) reduced anticipatory and sustained activity in the legs and upper body including left shoulder protraction (Fig. 6J-N). The tasks studied required participants to lift the violin with their left hand, rotate the violin to rest on the shoulder, turn the head leftwards onto the chin rest to support the weight of the violin between chin and shoulder rest, bring the bow to the violin and bow with the right hand to play. In the absence of external forces and torques, global angular and linear momentum are unchanged by segmental motion. However, through internal effort transmitted externally through the forceplate, task actions can perturb global balance including location of whole body center of mass (CoM) relative to base of support and rotation of whole-body mass about the CoM. Neck regulation was notable in minimizing the disturbing effect to global mass-rotation around vertical and forward axes through CoM (Fig. 6O-Q) and to lateral balance (Fig. 6R). Neck regulation reduced unnecessary transient upwards rotation (Fig. 6O), reduced sustained left CoM displacement (Fig. 6R), and reduced anticlockwise global mass-rotation around CoM within the frontal plane (AR) (Fig. 6P). Left CoM displacement increases gravitational moments [24]. AR from the initial symmetric orientation increases gravitational moments. Hence neck regulation improved global balance, reducing global cost.

IV. Discussion

This study used visual feedback of the neck muscles during performance of unskilled and skilled manual tasks, to investigate the relationship between voluntary regulation of the neck muscles and the involuntary construction of whole body motor output. The main results, summarized below, confirmed our three hypotheses:

H1: Neck muscle movement can be regulated voluntarily while maintaining task performance

H2: There is a causal relationship between voluntary regulation of neck muscles and global control of movement

H3: Proactive-selective inhibition targeted at the neck muscles reduces the global cost of movement

Using visual feedback, proactive-selective inhibition targeted at the neck muscles ("neck regulation") (Series E), achieved clear general reductions in anticipatory, transient and sustained neck muscle movement. The effect of neck regulation was distinct from the effect of gaze alignment (Figs. 5 and 6). Both neck regulation and gaze alignment resulted indirectly in uninstructed, task-independent changes in whole-body movement. Gaze alignment (Series C) reduced laboratory-referenced movement of the head and trunk at increased physiological cost (Figs. 6–9). By contrast, proactive-selective inhibition targeted at the neck muscles (Series E) resulted in changes in global movement not achieved through gaze alignment, with decreased physiological cost in muscle activities, skin conductance and compressive force on the violin chinrest, and with improved global balance.

A. The Voluntary Inhibitory Regulation of Neck Muscles

These results confirm the possibility of voluntary, selective inhibition of neck muscles without detriment to task performance. In these experiments, using visual feedback, participants in Series D had to see and associate changes in the image with different phases of the task such as raising arms, turning the head, securing the instrument and playing (*movement-visual association*). Note that participants were not instructed in the features of the US image. The instructions given ensured participants made their own associations based upon their own observations. Next, in Series E, using visual feedback for guidance, participants had to make the necessary changes in motor command that simultaneously reduced unnecessary neck muscle movement and achieved task performance (*proactive-selective inhibition*).

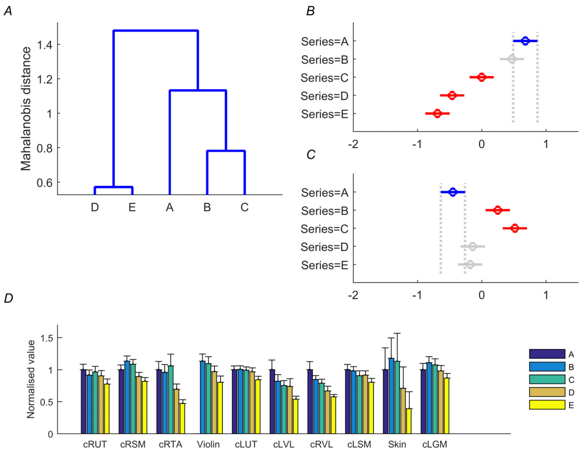

Fig. 9. **Indirect, effect of neck muscle regulation on cost**

A: *Mahalanobis* distance between series. Neck regulation had the greatest effect on cost and had a greater effect than gaze alignment. Relative to normal task performance (Series A, B) neck regulation (Series E) had a mean *Mahalanobis*distance of 1.9, whereas gaze alignment had a distance of 1.1. The distance of Series E from C is 1.2.

In common with the US and movement analyses, neck regulation and gaze alignment were associated with distinct effects on analogue quantities.

B. DF1 (55% variance) was most strongly associated with neck regulation (Series E), showed significant difference between series ($p < 0.0001$) with Series E, D, and C all significantly different from Series A.

C. DF2 (23% variance) was most strongly associated with gaze alignment (Series C). DF2 showed a significant difference between series ($p < 0.0001$), with only Series C and B significantly different from Series A. Trial scores from DF1 and DF2. Red indicates significant difference from Series A (blue).

D: Significant univariate effects of series. Corresponding to DF1 is a progressive reduction in all quantities from Series A to E. Corresponding to DF2, is a deviation from the overall progressive change through Series A-E maximized in Series C This DF2 pattern shows gaze alignment to be associated with an increased transient activity (accumulated positive change) in arm and leg muscles, increased skin conductance and increased chin rest compression. The structure matrix confirms global reductions in transient (cEMG) and sustained (EMG) muscle activity associated with DF1 and increases associated with DF2. At $p < 0.05$, there were no significant interactions between series and task.

Bars show means ±95% confidence intervals. Quantities significant at alpha< 0.05, are ranked left to right with most significant left. Quantity labels are UT-Upper *trapezius*; SM-*semimembranosus*; VL-*vastus lateralis*; TA-*tibialis anterior*; GM-*gastrocnemius medialis*; Violin–violin chinrest strain gauge; Skin–skin conductance.

Acquiring movement-visual associations (Series D) caused some reduction in neck muscle movement (Fig. 5B, D). Since the procedure of Series E was not revealed during Series D, the implication is that observation and formulation of associations between self-movement and neck muscle movement had some, but less, effect on neck muscle action. Also focus of attention to the blank monitor did not replicate the reduction in neck muscle movement observed during Series E (Fig. 5D, Fig. 6C, D). Use of the information presented on the monitor to reduce neck muscle movement (*proactive-selective inhibition*) required coupling of observation with motor command.

The natural, effectiveness of regulation of the neck muscles observed in Series E raises the possibility that following training with feedback, voluntary, regulation of the neck muscles would be possible without feedback. Clearly there is potential for developing augmented feedback, building upon the recently developed methods of ultrasound analysis [20].

B. The Indirect, Involuntary Effect of Inhibitory Regulation of Neck Muscles on Whole Body Movement

We emphasise that no instructions were given to participants regarding how to change their task performance. Participants were never told to change the way they performed the tasks. In Series E, participants were instructed to minimize neck muscle movement on the US monitor while performing the task. Confirmation that participants engaged in a process distinct from previous Series A-D is provided by the increased duration to produce sound in Tasks 4-6, though the mechanical speed of hand movement was unaltered (Figs. 1 and 2 Supplementary Results). Changes in whole body performance, of which participants were largely unaware, were previously unknown and unplanned, and were thus self-chosen by the participants. After completion of the entire experimental series, before leaving the laboratory, participants were shown Vicon motion system recordings of their movement. Most expressed surprise upon seeing their movement patterns in normal playing (Series A, B) and also when minimizing neck muscle movement (Series E). The change between normal playing (Series A, B) and Series E was regulated by attending to and minimizing neck muscle movement. We can therefore say that proactive-selective inhibition of the neck muscles (neck regulation) caused the involuntary change in whole body movement.

We observed two indirect benefits to voluntary, inhibitory neck regulation.

The first benefit is one of learning. Sensorimotor control that is highly automated through reinforcement learning and training is habitual and inaccessible to modification [25]. Furthermore, the automated solution, refined by experience, typically lies within a multi-dimensional local optimum, in which local departures usually worsen performance. When performance is important, immediate reward provides little incentive to learn. We observed that, through the procedure of Series E, participants demonstrated execution of performance previously unobserved in numerous trials during familiarization and control series A-D (Fig. 6). The generation of new behavior was uncomplicated, relatively instantaneous and self-chosen (unsupervised).

The second benefit is one of reducing cost and regulating performance. The effect of neck regulation can be summarized as reducing effortful, unnecessary movement throughout the body (Figs. 6 –9). Downward flexion of the head and compressive chinrest force was reduced. Forward protraction of the left shoulder towards the violin was reduced. Forward protraction and elevation of the right shoulder was reduced. Anticipatory and transient task-related activity in the leg muscles was reduced. Disturbance to global balance (CoM location) and global angular momentum by the task was reduced. Skin conductance measures sympathetic arousal. Sympathetic arousal reflects central integration of psychophysiological input anticipating future demand for effort [26]. Series E reduced the task related rise in skin conductance. We infer that neck regulation regulated performance by reducing the physiological cost, altering control of the whole body to allow smoother performance with improved global balance. Improved performance at reduced cost provides its own reward for subsequent reinforcement.

C. The Mechanism by Which Direct Regulation of the Neck Muscles Influences Construction of Whole Body Movement

During Series E, we observed simultaneous effects in muscle and movement, throughout the body (legs, arms, neck) early in the arm raise (Fig. 5). We infer that sensorimotor control is altered, not just biomechanics. Changes in neck muscle observed using US, referred to as muscle “movement”, include changes in active contraction of the neck muscles and passive shape change caused by the action of other muscles. For example changes in head rotation relative to the trunk would cause passive changes potentially observable in all neck muscles. The neck muscles viewed using US include upper *trapezius*, *splenius*, *spinalis capitis*, *spinalis cervicis* and the intrinsics. These muscles alone cannot explain the global changes we observed including shoulder protraction, trunk rotation, leg activations and chin rest compression. The global changes in movement require altered action from multiple muscles including, but not limited to, synergistic contributions from the neck muscles observed by US.

Trial and error feedback provides one possible mechanism associating neck regulation with whole body movement. Instruction to minimize neck muscle movement provides a criterion to alter the central selection of motor output. Trial by trial, the central selection is altered to reduce neck muscle movement change observed using US. This result is achieved by coordinating change in all muscles to alter neck muscle movement. Furthermore, muscles crossing the neck respond to many whole body movements. Since, the neck lies at the root of kinematic chains linking the head, trunk, and arms, most movements including looking, reaching and grasping, balance and locomotion will produce changes observable in the neck muscles. Neck muscles change if the head moves or if the arms move. Hence, in general, minimisation of neck muscle movement (active or passive) will minimize whole body movement although exceptions to this generalization are possible. For example, increasing axial rotation of the trunk relative to the pelvis and laboratory may minimize axial neck rotation to maintain alignment of gaze with the US monitor.

Feed-forward processes provide a second possible mechanism, one in which the current and planned, future state of the neck muscles, informs construction of the global motor plan. The movement of any segment occurs relative to its parent segment. The control of child segments depends upon the current state and planned futures states of the parent. Constraints in position and force defining the control of segments accumulate along the kinematic chain from the stabilising reference segment to the distal end segment. Any specification applied at the neck, has consequences for the planning and control of segments distal to the neck.

For example, since, overlapping, bi-articular muscles cross all joints from the head/neck to the finger (e.g., *trapezius*, *triceps, extensor digitorum, flexor digitorum*), we propose reduced co-activation specified at the neck would require reduced co-activation recursively down an open chain, or within a closed chain, to maintain net joint moments. Consequently specifying reduced co-activation across the neck joint would predict reduced compression of the violin between chin and shoulder rest.

For example, raising, positioning, securing and playing the violin requires simultaneous control of all body segments to ensure dynamic balance. Proactive minimisation of anticipatory neck muscle action and head movement would predict reduced anticipatory control of the legs and trunk as observed during the interval -1 to 1 s in Series E (Fig. 5).

The mechanical rationale for the dependence of control upon the neck is mirrored by the biological design of the human sensory system. Accurate, economical motor control requires a known reference. The reference provides a sensory frame from which to estimate configuration. Normally, the ground provides a reference. Through visual, vestibular and auditory sensation, the head provides a second sensory reference frame. Proprioception is essential for extracting body motion from head-referenced visual, vestibular and auditory sensation [12]. The main mass of the body lies close to the trunk and the neck is the primary articulation defining trunk location from the head. Along the kinematic chain proceeding from the head, proprioception of the neck provides the first, most predictive head-referenced estimate of body location justifying the high biological investment in the abundance, density and elaborate structure of neck muscle spindles [27], [28]. A more differentiated estimate of configuration accumulates through proprioception of additional joints along the extended proprioceptive-kinematic chain [29]. Since the neck lies at the root of this chain, proprioceptive inaccuracy at the neck influences every dependent estimate. Minimization of anticipatory, neck and head movement would simplify planning the control of dependent, segments.

Almost all quantities (US, kinematic and analogue) showed no interaction between the two factors, Series and Task. The only exceptions were thoraco-pelvic rotation and right ankle axial rotation. Since task order was consistent, rather than randomized, this lack of interaction implies the effect of Series did not change through time. This result lessens support for the trial and error feedback mechanism, as this explanation predicts the effect of Series would increase through time. Hence while both mechanisms are possible, our results favour the feedforward mechanism in which planned neck action informs the global plan. Our informal observation that neck regulation produced almost instant results, also favours the feedforward mechanism.

In summary, many global muscle activation/movement patterns are associated with changes in neck muscle state. This follows the location of the neck proximal to outgoing motor kinematic chains and incoming sensory chains of the head, upper limbs and trunk. Selective inhibition of the neck muscles imposes a proximal, constraint on the global motor plan, forcing a change in highly automated sensorimotor control. The proximal location ensures global influence. The criterion, inhibition of unnecessary action, ensures reduced cost while facilitating task relevant variation.

D. Reconciliation With Theory of Focus of Attention

There is evidence that an internal focus induces a conscious type of control, causing individuals to constrain their motor system by interfering with automatic control processes whereas an external focus allows automatic control processes to regulate movement [14], [15], [17]. One assumption within this literature is that automated control is superior both in performance effectiveness and in cost of performance. A second assumption is that conscious control adds constraints detrimental to established performance.

During Series C, participants aligned gaze at the blank US monitor while performing the instructed tasks. Results from Series C support the idea that the addition of constraints was detrimental since the cost of performance increased.

During Series E, participants consciously applied the constraint of minimizing movement in the neck muscles. The US monitor provided augmented feedback i.e., external presentation of intrinsic feedback. The result was generation of new behavior in proximal components of the movement, without detriment to task performance with lowered immediate cost and with reduced movement associated with chronic, task specific injury [30]–[32]. These results undermine the assumption that automated control is superior and also the assumption that conscious control adds constraints detrimental to performance.

During Series E, the inhibitory nature and proximal target of this conscious control removed automated constraints limiting performance. Our interpretation is that participants were unaware of the constraints self-imposed by their learned sensorimotor mappings. Automation had restricted their behavior to a relatively fixed set of proximal segmental movements consistent with the end goal. Instruction to minimize unnecessary neck muscle movement required inhibition of all automated solutions causing unnecessary neck muscle movement, allowing consideration of new solutions. Our proposed mechanisms suggest the criterion simplified planning, ensured acceptable solutions were less effortful and, we suggest from personal experience of the experiment, allowed increased external focus of attention on the end goal.

While involuntary automated control is learned [14], [15], [17], sensorimotor learning works by immediate reward [1]. The maladaptive nature of learned, automated

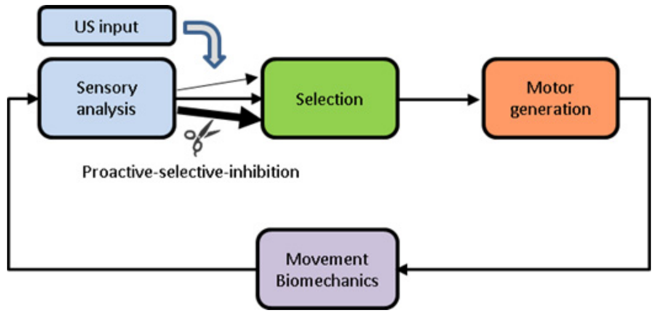

Fig. 10. **Proposed process model applying voluntary inhibitory neck regulation to regulation of chronic conditions.** This perception-action model shows sensorimotor control operating as a closed loop process with selection occurring inside the feedback loop. Selection: highly facilitated (automated) sensorimotor responses (thicker line) pass trans-cortically, bypassing the slow frontal-striatal selection loops. Given sufficient global or selective inhibition, slow frontal-striatal loops have time for goal evaluated selection [e.g., 25]. The "**scissor**" indicates the effect of proactive-selective-inhibition targeted at the neck muscles to inhibit highly facilitated, automatic, sensory-motor associations. All processes, sensory analysis, selection, motor generation, movement biomechanics adapt according to their prevailing input and output. Feedback has the potential to amplify and diminish the (mal)-adaptive consequences of selection. Results (Figs. 5–9), show that direct voluntary inhibitory regulation of neck muscle can indirectly regulate global motor function. The proposal is that proactive-selective-inhibition of neck muscle can regulate vicious positive feedback leading to pain, injury and performance limitation. Augmented feedback can assist learning voluntary, inhibitory regulation of the neck muscles.

control is not apparent immediately but evolves over time. For example, the cumulative effects of biomechanical loading, and neural adaptation such as de-differentiation of receptive fields by repetitive attended behavior [33], were not available when the learning was formulated and consolidated.

E. The Relevance of Voluntary Inhibitory Neck Regulation for Indirect Regulation of Body Function in Health and/or Disease

Violinists are subject to medical problems that are specifically related to the physical and psychological demands of their profession [30] with the majority reporting musculoskeletal symptoms affecting mainly the upper extremities, particularly the shoulders, neck, and back [30], [34]. The fact that sensorimotor control patterns are highly automated, combined with the fact that musicians depend upon their learned patterns for performance and livelihood means that changing engrained sensorimotor control is difficult. The pattern eliminated by neck regulation (protracted shoulder, neck flexion, and chinrest compression) is indeed that associated with chronic pain, injury and performance limitation in violinists [30]–[32]. Hence voluntary, inhibitory regulation of the neck muscles has potential therapeutic value. Briefly, we outline a theoretical basis generalizing the potential of this result.

Muscle action and movement operate within a feedback loop that includes the nervous system, muscles, tendons and biomechanical interaction with the environment. This idea of a perception-action cycle is well-established. Fig. 10 shows processes of sensory analysis, selection, motor output, and biomechanical-environmental interaction as a closed-loop dynamic system [35]. Multiple movement patterns are compatible with task performance but have differing physiological costs including differing consequences in location and extent of biomechanical loading and fatigue. Different patterns also have differing cumulative cost in sympathetic arousal. Cortical receptive fields are known to adapt depending upon attention and the information content of the repetitive sensory input [33]. Within this closed loop process (Fig. 10) the consequences of selection are subject to feedback and will amplify or diminish through time, depending upon whether the feedback loop gain is positive or negative. Usually, positive feedback is associated with maladaptation leading to long term disorder. For example, positive feedback within this loop has been shown to reinforce the development of focal dystonia, chronic pain and injury [33].

The new evidence of this paper is that voluntary regulation of the neck muscles has a global regulatory benefit. Specifically, proactive-selective inhibition of the neck muscles inhibits unnecessary anticipatory, transient and sustained output, improves global balance and reduces cost. Our interpretation of the method and results proposes these changes were achieved by disfacilitating fast, automated sensory-association-motor pathways and by utilizing slow, frontal striatal pathways which allow new learning through their mechanisms of selection and reinforcement learning [4], [25], [36]–[39].

While these results apply to this study, the proposed mechanism applies generally to all activities which engage muscles crossing the neck. Improved global balance and reduced cost is relevant to high performance sports involving goal oriented throwing, hitting and kicking. Potentially, the proposed mechanism applies to many conditions in which sensorimotor mapping is automated and/or associated with chronic pain, injury and performance limitation, and where positive feedback reinforces the symptoms. The proposed mechanism opens the loop by inhibiting the automated sensorimotor control, allows new sensorimotor mapping, and provides negative feedback countering conditions reinforced by vicious cycles of positive feedback. The results suggest a role for technology in training voluntary regulation of the neck muscles.

ACKNOWLEDGEMENTS

The authors thank the anonymous participants for generously giving their time and interest for these experiments. They thank D. Richards for his technical support with custom designed equipment. They also thank BAPAM (www.bapam.org.uk) and I. MacDonald for their support of AL and for their help in recruiting participants for this study.

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