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Effect of muscle fatigue on internal model formation and retention during reaching with the arm

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Takahashi, Craig D., Dan Nemet, Christie M. Rose-Gottron, Jennifer K. Larson, Dan M. Cooper, and David J. Reinkensmeyer. Effect of muscle fatigue on internal model formation and retention during reaching with the arm. *J Appl Physiol* 100: 695–706, 2006. First published October 27, 2005; doi:10.1152/japplphysiol.00140.2005.—The motor system adapts to novel dynamic environments by forming internal models that predict the muscle forces needed to move skillfully. The goal of this study was to determine how muscle fatigue affects internal model formation during arm movement and whether an internal model acquired while fatigued could be recalled accurately after rest. Twelve subjects adapted to a viscous force field applied by a lightweight robot as they reached to a target. They then reached while being resisted by elastic bands until they could no longer touch the target. This protocol reduced the strength of the muscles used to resist the force field by ~20%. The bands were removed, and subjects adapted again to the viscous force field. Their adaptive ability, quantified by the amount and time constant of adaptation, was not significantly impaired following fatigue. The subjects then rested, recovering ~70% of their lost force-generation ability. When they reached in the force field again, their prediction of the force field strength was different than in a nonfatigued state. This alteration was consistent with the use of a higher level of effort than normally used to counteract the force field. These results suggest that recovery from fatigue can affect recall of an internal model, even when the fatigue did not substantially affect the motor system's ability to form the model. Recovery from fatigue apparently affects recall because the motor system represents internal models as a mapping between effort and movement and relies on practice to recalibrate this mapping.

motor adaptation; robot

FATIGUE IS A COMMONLY EXPERIENCED condition that results from a period of intense or prolonged physical activity and is characterized by a reduced capacity to exert muscular force. Fatigue is associated with mechanisms that are diverse and not completely understood but can develop due to factors proximal to the neuromuscular junction (20, 54, 61) or to factors involving the peripheral nervous system and muscle (1, 23, 35, 51). Fatigue slows muscle fiber conduction velocity (4, 43, 46), prolongs twitch duration (2, 18, 45, 64), and increases the neural activation required to produce a given force (8, 24, 26, 31, 63). Fatigue can affect motor performance in skilled activities such as targeted throwing (17), stoop lift (22), tennis (12), and balancing on an unstable surface (29).

A key strategy used by the nervous system to adapt to altered dynamic environments is to form an internal model, a feedforward neural mapping between limb state and muscle activations, which allows the nervous system to predict the muscle activations needed to achieve a desired movement in environments characterized by patterns of forces applied to the limbs (9, 39, 56). Several research groups recently have studied internal model formation using an experimental paradigm established by Shadmehr and Mussa-Ivaldi (56), in which a lightweight robotic device was programmed to apply a force field to the arm during reaching (reviewed in Ref. 49). A typical force field is a viscous curl field that pushes the arm perpendicular to the movement direction with a force proportional to the hand speed. Subject's reaching trajectories are initially curved when such a field is applied (the "direct effect") but then gradually straighten over the course of tens of reaches (16, 28, 37, 59, 60). If the field is then unexpectedly removed, the reaching trajectory is curved in the mirror-symmetric fashion to the direct effect, called an "aftereffect," indicating that the subject learned an internal model of the force field and was using it to predictively compensate for the field. Once an internal model is learned, it can be recalled following a period when it is not accessed (3, 7, 55). This process, called "retention," is partially characterized by a reduction in the size of the direct effect when a person revisits a force field. Retention of internal models likely assists us in using tools or moving in novel dynamic environments, such as water, following a hiatus. The process of retention should be distinguished from "consolidation," a process in which an internal model becomes "permanent" and is not modified by adaptation to a different environment (3).

Internal models must necessarily incorporate information about nerve and muscle properties to accurately estimate muscle forces. Because these same properties are known to be affected by fatigue, it follows that fatigue may affect the ability of the nervous system to form, implement, or recall internal models. Understanding the effect of fatigue on the use of internal models is important for understanding and optimizing exercise, sports training, and rehabilitation, in which it is common for a person to practice a particular motor task while fatigued, but then seek to perform the task later in a rested state. It has not been well defined how the practice of a dynamic motor task in a fatigued state benefits performance of the same task after rest.

The goal of this study was, therefore, to test how fatigue affects the ability of healthy adults to acquire and recall an

internal model of a novel dynamic environment. We were particularly interested in whether an internal model acquired in a fatigued state could be appropriately recalled on revisiting the same environment after a period of rest. Because internal models are structured as an association between visited limb states (e.g., joint positions and velocities) and experienced forces (9, 56), they must necessarily incorporate information on the force-producing capacity of muscles. Because the force output of fatigued muscle is partially restored after rest, it follows that this recovery might affect the ability of the nervous system to recall an internal model that was acquired in a fatigued state. If accurate recall is possible without movement of the limb, this would suggest that the nervous system internally monitors the force production capacity of muscle to update its internal models. If accurate recall requires movement of the limb, then this would suggest that the nervous system uses a type of system identification process that relies on actual experience of the current relationship between muscle activation and muscle force to recalibrate its internal models following fatigue.

MATERIALS AND METHODS

Twelve healthy subjects (ages 22–40 yr; 6 men and 6 women) participated in the study, which was approved by the University of California Irvine Institutional Review Board. Subjects provided written, informed consent.

General Protocol

The subject held the end of a robot and made repeated reaching movements to a physical target positioned in front of their body (Fig. 1A). For some reaches, the robot applied forces to the hand, producing a specific dynamic environment (i.e., pattern of environmental forces) during the reach. The force patterns were applied during sequential sets of trials called "stages" (Fig. 1B). Each stage had a particular purpose and was distinguished by the specific force patterns applied to the subject. For example, the purpose of the first stage [called *null 1* (N1)] was to measure baseline reaching trajectories, and so the robot did not apply forces to the hand during *trials 1* through *20*. The overall sequence of stages was designed to test motor adaptation and retention twice, with an intervening period of fatiguing exercise (Fig. 1B).

Details of Reaching Procedure

The seated subject held the end effector of a three degrees-of-freedom lightweight robot arm (PHANToM 3.0, SensAble Technologies) with the dominant hand (the right hand for all subjects; Fig. 1A). Each subject started with the reaching hand resting on the lap. A computer-controlled light-emitting diode prompted the subject to raise the hand to a physical "start" target (the tip of a small compliant plastic pointer) positioned two hand widths out from the center of the sternum. After attaining the start target (moving the robot end effector to within a distance of 20 mm from the target for at least 0.5 s), the computer sounded a tone, prompting the subject to reach out to a similar "finish" target, aligned in the anterior direction and positioned just inside the boundary of the reaching workspace (i.e., the target distance was scaled to the subject's arm length and was positioned in front of the subject or in the $-z$ direction). The average distance between the start and finish targets across all subjects was 28.1 ± 4.2 cm. After the subject attained the finish target (same criteria as the start target), the computer sounded another tone, prompting the subject to return the hand to the lap for a 1-s rest. After each movement, the computer provided visual feedback on the reach speed (just right = desired reach time $\pm 5\%$; too fast; or too slow). Each of these reaching movements was termed a "trial." The desired reach time was determined from a test conducted at the beginning of the experiment in which the subject performed the same reaching exercise, only reaching as fast as possible to the finish target (20 trials). To scale the experimental conditions to each subject's maximum movement speed, the desired reach time was set arbitrarily to be 167% of the mean of the shortest three reach times (i.e., the 3 fastest reaches); this value required brisk but not fast-as-possible reaches.

Detailed Description of Stages

Each subject reached repeatedly in nine sequential stages. The stages can be viewed as comprising a first retention test, an exercise protocol, and a second retention test.

First retention test. N1. In the first stage (N1), the robot did not actively apply forces to the subject for 20 trials, thus providing a baseline measure of reaching performance. We will use the term "null" to refer to stages in which the robot did not apply forces to the arm.

EXPOSURE 1. In the second stage [*exposure 1* (E1)], the robot applied a force field to the arm for 20 trials to measure the baseline adaptive performance of the subject (see detailed description of force field below). We will use the term "exposure" to refer to stages in which the robot exposed the subject to a force field. We chose to measure adaptation for 20 trials because several studies have demonstrated relatively complete adaptation over trial periods of this length (16, 28, 37, 59, 60), and we desired to limit the overall length of experiment. After this stage, subjects rested the reaching hand in the lap for 10 min (matching the rest to be given in the second retention test, after fatiguing exercise).

EXPOSURE 2. After rest, subjects again moved in the force field for 20 trials [*exposure 2* (E2)]. We used the first movement during this stage to assess the level of retention of the internal model learned during E1. In other words, if the subject moved without trajectory error the first time in the field after rest, it would indicate that he had fully retained the internal model learned before rest.

NULL 2. Subjects now reached in a null field for 20 trials (*null 2*), allowing measurement of the aftereffect and providing a "washout" of the internal model from E2.

Exercise protocol. Following the first retention test, subjects executed one of three possible exercise protocols: fatigue right (FR), fatigue left (FL), and no fatigue (NF). For the FL and FR protocols, the fatiguing exercise was reaching to the target with elastic bands that pulled the arm to the left or right, respectively. For the NF protocol, the exercise was reaching to the target without resistance. The goal of this exercise stage was to fatigue the subject's muscles so that the subject's adaptive ability in a fatigued state could be measured, as well as retention following recovery from fatigue. The NF exercise protocol served as a control condition to measure the effect of intervening time without fatigue.

Second retention test. NULL 3. After the fatiguing exercise protocol, a second retention test was performed. The elastic bands were first removed, and the subject then reached in a short null field (*stage 6* or *null 3*) for five trials to wash out any effect of the force field created by the elastic bands, but without allowing appreciable rest.

EXPOSURE 3. Subjects next adapted to the force field for 20 reaches [*exposure 3* (E3)]. They then rested for 10 min, just as in the first retention test. This now set the stage for measuring retention following recovery from fatigue.

EXPOSURE 4. After rest, subjects then reached for another 20 trials in the force field to measure retention [*exposure 4* (E4)]. The first reach in E4 was used to indicate the amount of retention of the force field that had been learned in E3 before rest.

NULL 4. Subjects finally reached for 20 trials in the null field, providing a measure of the aftereffect of adaptation and washing out the exposure to E4 (*null 4*).
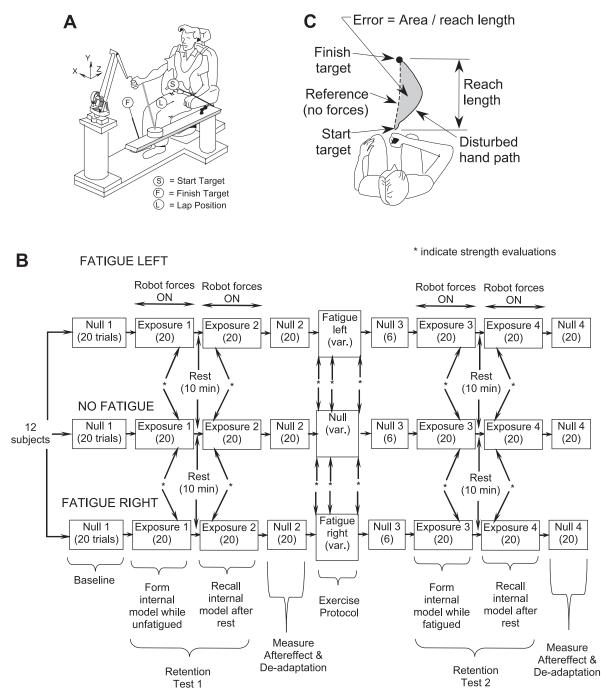
Fig. 1. Summary of experimental setup, protocol, and measures. *A*: subjects reached while holding the end of a lightweight robot arm that allowed the hand to move in 3-dimensional space. *B*: subjects performed 2 tests of retention, separated by an exercise protocol: the fatigue left (FL), fatigue right (FR), or no-fatigue (NF) protocol. Retention was tested by having subjects adapt to a viscous force field generated by the robot, then rest for 10 min, then move again in the force field. The first retention test was given by force field *exposures 1* (E1) and *2* (E2), and the second by *exposures 3* (E3) and *4* (E4). In the FL exercise protocol, the subjects reached to the target while an elastic band pulled the hand to the left until they could no longer reach the target. In the FR protocol, the band pulled the hand to the right. In the NF protocol, they reached without resistance. Subject strength was checked at various points throughout the protocol (indicated by asterisks). Reaches were made in null fields (i.e., robot applying no force) before and after the retention tests to measure the baseline reaching trajectory [*nulls 1* (N1) and *3* (N3)] and to washout the learned internal model [*nulls 2* (N2) and *4* (N4)]. *C*: summary of experimental measures.

Detailed Description of Exposure Stages

During the force field exposure stages (E1, E2, E3, and E4), the robot applied a viscous force field according to the equation

$$F = k\bm{b} \times \mathbf{v} \qquad (1)$$

where $k = 1$ (scalar gain), $b = [0\ 3.65\ 0]^{\mathrm{T}}$ N·s/m is a three-element

vector that points straight up per reference frame (Fig. 1*A*), v is a three-element vector ($\epsilon\ \mathbf{R}^3$) representing the velocity of the subject's hand in space, and F (the force applied by the robot) is a three-element vector formed from the cross-product of b and v (and multiplied by gain k). The resulting force, applied only during the outward reach, pushed the subject's hand leftward (orthogonal to the plane spanned by b and v).

Detailed Description of Exercise Protocol

Each subject performed the entire sequence of nine stages three times, one time per day for different days. Each time they performed the sequence, they experienced a different exercise protocol: the FL protocol, the NF protocol, or the FR protocol (Fig. 1*B*). The FR protocol was added as a control condition following initial analysis of the data from the first two protocols. Only 10 of the original 12 subjects were available to perform this protocol on a third day.

In the FR and FL protocols, each subject performed the reaching task against resistance provided by stretched elastic bands (Medicordz) attached to the wrist. The other end of the elastic band was mounted to the center of a six-axis force transducer (Assurance Technologies, Theta model), which was positioned 76 cm to the left (in the lateral, or $-x$, direction for the FL protocol) or to the right (or $+x$ direction in the FR protocol) of midline. The level of resistance during the task ranged from ~65% of maximal strength at the starting point (77.9 ± 20.7 N) to 55% at the finish target (60.1 ± 16.5 N), where strength was measured by having subjects pull against the bands perpendicular to the reaching direction, starting from the start target. The forces applied by the robot were 3.4 ± 1.6 N. Each subject reached until he/she was no longer able to reach the finish target (i.e., complete the task) within a period of 6 s. The subject was then asked to attempt to reach for several more trials. Subjects reached an average of 42 ± 15 times in the FL protocol (range: 20–64 times) and 46 ± 22 times in the FR protocol (range: 16–65 times).

The rationale for including the NF protocol was that it served as a control condition to measure the effect of intervening time without fatigue. The stages for the NF exercise protocol were identical to those of the FL and FR protocols, except that the subjects reached without elastic bands attached and without the robot applying forces to the hand. The number of reaches for the NF protocol was matched to the number of reaches the subject achieved in the FL protocol.

The force field direction was the same for both the FL and FR protocol because we wanted to make sure that any observed retention effect was not due to a generalized or systemic effect of exercise. In other words, subjects performed one protocol, which fatigued the muscles, that was primarily used to compensate for the force field (the FL protocol) and one that did not (the FR protocol).

Strength Evaluations

Strength evaluations were also performed at various points throughout the experiment (see asterisks in Fig. 1*B*: 3 trials before the end of E1; 3 trials after starting E2; before starting the fatiguing field; 10 trials into the fatiguing field; after last trial in fatiguing field; 3 trials before end of E3; and 3 trials into E4). Strength evaluations were performed by attaching elastic bands to the wrist and asking the seated subject to reach up to the start target and then pull the hand to the right ($+x$ direction) with as much force as possible in the FL protocol. Subjects pulled the hand to the left in the FR protocol. The other end of the elastic band was mounted to the center of a force transducer as described above. Subjects were constrained by a torso harness and were asked not to "jerk the arm" or "lean the body." The resistance (spring constant) of the elastic bands was adjusted by varying the number and type of bands so that the subject's maximum effort would result in a lateral hand position that was nearly aligned (along the *z* direction) with the right shoulder for the FL protocol and with the left shoulder for the FR protocol. The same resistance was also used in the fatiguing field. Another physical target was placed laterally to the start target just beyond the shoulder position at an "unreachable" point in space to provide motivation and to specify the target pulling direction. The experimenter provided verbal encouragement during each strength evaluation and also during the fatiguing stage. Strength evaluations were also performed at the beginning of the experiment for each subject. The strength value was taken to be the maximum of three attempts, with ~1-min rests between attempts. Baseline strength was taken to be the strength evaluated three trials before the end of E1.

Data Analysis

A computer sampled the three-dimensional position of the robot tip (and thus the subject's hand position) at 1,000 Hz, as inferred from rotational sensors at the robot joints. Several outcome measures were calculated from this record of the subject's hand position. Many of these measures were derived from a measure of reaching error, the average difference between a given hand path and the normal hand path for the subject.
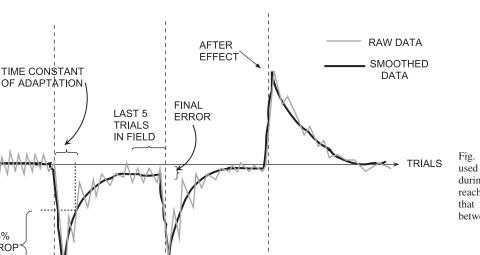
Reaching error calculation. Because the force field pushed the hand to the left or right, disturbances to the reaching trajectory were mainly in the horizontal plane. Statistical analysis indicated that trajectories were not significantly disturbed in the vertical direction on initial exposure to or removal of the field. Thus reaching errors were quantified as the area between the reach path and a reference path projected onto the horizontal plane (*x-z* plane; Fig. 1*A*) divided by the distance between the start and finish targets (Fig. 1*C*). The resulting geometric measure of error is the spatial average of the lateral deviation away from the reference path. Reach paths that were to the right of the reference path were given positive values, whereas those to the left were given negative values. The reference path was selected to be the average path of the trials in the last half of the N1 stage (*trials 11–20*). The average was computed by aligning the path data to an initial velocity threshold (75 mm/s) and computing the mean across the corresponding sampling points. For these trials, the subjects had presumably acclimated to using the robot but still had no perturbing force field applied to them. Averaged hand paths were computed in the same fashion over the applicable range of trials and subjects.

Group-averaged reaching error. We calculated the mean of the reaching errors across subjects throughout the experiment. We term this the "group-averaged reaching error." Each element of the group-averaged reaching error was computed by taking the mean across all subjects for the corresponding trial.

One issue that arose in calculating the group-averaged reaching errors was that subjects reached in the fatiguing field until they could no longer perform the task, so each subject reached a different number of times in the fatiguing field. To compute the average reaching error across subjects, the fatiguing field data was rescaled in time, and the reaching error was fitted with splines as a function of trial. We chose the range of the fatiguing field trial to be 81–145 for all subjects, regardless of the number of actual trials performed in the field. *Trial 145* was chosen because this was the maximum trial number at which fatiguing exercise stopped for any subject. The spline-fitting process essentially rescaled the trials variable so that it reflected percent time into the fatiguing exercise, with *trial 81* being 1% into fatigue exercise and trial 145 being 100% into fatiguing exercise. The group-averaged reaching error was obtained by computing the mean across corresponding scaled trials, effectively averaging trials along the same percentage of trials into the fatiguing field. This technique also provided a way of aligning data in subsequent stages (e.g., the *null 3* stage always starts at *trial 146*). A similar aligning technique was used when group averages of other outcome measures, described next, were taken.

Outcome measures used to describe motor adaptation to the force field. Several kinematic measures of reaching were used to quantify the subject response to the force fields (summarized in Fig. 2). The "direct effect" in response to a force field was quantified as the reaching error in the first trial of the force field. "Final error" was quantified as the mean reaching error in the last five trials of the field exposure. "Performance improvement" was quantified as the percent difference in the reaching error between the first reach in the field and the final error. The aftereffect was quantified as the reaching error in the first trial after a force field was removed (*trials 61* and *191*).

We also quantified a "time constant of adaptation" of the reaching error as subjects adapted to the force fields and de-adapted after removal of the force fields. The time sequence of reaching errors of individual subjects was highly variable and typically not amenable to

Fig. 2. Terminology and outcome measures used to quantify adaptation to the force field during a single retention test. The pattern of reaching error in this figure is consistent with that found when subjects rested for 10 min between E1 and E2 to the force field.

curve fitting to raw data. Thus the time constant of adaptation was determined by first smoothing the reaching error data of each subject with a causal moving average of a nine-point window. The time constant of adaptation was then quantified as the number of trials before the smoothed data dropped 63% from the initial maximum error.

Outcome measures used to describe reaching quality during exercise. As subjects fatigued during the exercise protocol, the quality of their reaching movements degraded. Movement quality was assessed by examining movement smoothness and path length. "Normalized path length" was quantified as the reaching path length in space divided by the distance between the start and finish targets. Normalized path length would be equal to one if the subject moved in a straight line to the target and greater than one if the path exhibited fluctuations. Smoothness was quantified by "velocity peak count," which was the number of peaks in the speed profile (i.e., the magnitude of tangential velocity vs. time), with fewer peaks indicating a smoother movement. Peak counting was performed on conditioned data to account for noise and peak size. To avoid counting peaks that were the result of noise, the speed profile was filtered using a zero-phase forward and reverse second-order digital Butterworth filter at a frequency of 20 Hz. To place a minimum size requirement on the peak magnitude, a base speed profile was determined by similarly filtering the speed profile at 6 Hz and establishing a dual threshold of $\pm 0.5\%$ of the peak speed about this base. Only those peaks of the 20-Hz-filtered speed profile that exceeded this threshold were counted, effectively placing a minimum size requirement on the velocity peaks. Since subjects moved progressively more slowly as they tired in the field, the "velocity peak rate" was also calculated to provide a measure of smoothness that was independent of movement time. Velocity peak rate was the number of velocity peaks divided by the reach time. To examine the source of these characteristics within different phases of the movement, these variables were evaluated for the entire movement, the first 90% of outward movement (i.e., approximately the ballistic phase), and the last 10% of outward movement (i.e., approximately the target acquisition phase). These values were selected because subjects typically showed persistent difficulty attaining the target in the last 10% of outward movement. The zero crossing on the far side of the speed profile (47) could not be

used to define the division of the two movement phases due to the lack of smoothness in movement in the fatiguing field.
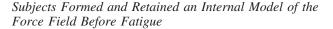
Statistical analysis. Statistical analysis was done using a commercial statistical analysis program (SPSS). For all analyses, data points exceeding 1.5 standard deviations away from the group mean were defined as outliers and were removed in a single iteration before statistical testing. To test for the presence of direct effects and aftereffects, the magnitude of the direct effect or aftereffect was compared with zero using a *t*-test, for each of the three exercise protocols, with a Bonferroni-corrected significance level (i.e., the significance level was set to be $0.05/3 = 0.17$). The effect of exercise protocol on internal model retention was analyzed using a mixed-model ANOVA, with the repeated measure being the direct effect in the four field exposures (E1, E2, E3, E4) and the within-subjects factor being the exercise protocol (FL, NF, and FR). Planned comparisons were used to compare the direct effect in E2 to E1 (a test of retention in the first retention test), direct effect in E4 to E3 (a test of retention in the second retention test), and direct effect in E4 to E2 (a test of the effect of the exercise protocol on retention). A mixed-model ANOVA was also used to analyze strength changes before fatigue, at the end of fatigue, and in E3 and E4. A multivariate repeated-measures ANOVA was used to determine the effect of exercise state on the three measures of movement quality (number of peaks, peak rate, and normalized path length) with follow-up, Bonferroni corrected *t*-tests for pairwise comparisons. Finally, a multivariate repeated-measures ANOVA was used to determine the effect of exercise state on the key measures of adaptation ability: the time constant of adaptation, percent reduction in reaching error, final reaching error, and aftereffects following exposure to the force field.

RESULTS

Twelve healthy adults performed two tests of motor retention, separated by an exercise protocol: the FR, FL, or NF protocol. Retention was tested by having the subjects adapt to a viscous force field generated by a lightweight robot, then rest for 10 min, then move again in the force field.
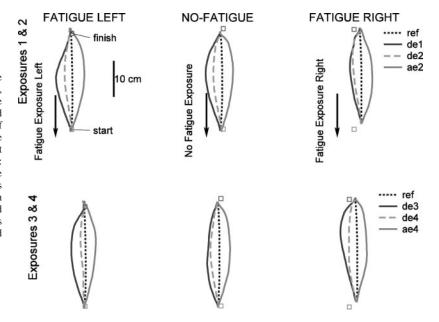
Fig. 3. Direct effects and aftereffects due to exposure to the force field. Plots show an overhead view of the hand paths, averaged across subjects, during the first reach in each force field exposure (direct effect) and the first reach in the null field (aftereffect). The dotted reference path is the average path of *reaches 11–20* in the first null field. The legend labels define which exposure the effect was measured in: de1, direct effect during force field E1; ae2, aftereffect following E2, etc. *Left*: for the FL protocol, subjects exhibited partial retention of the internal model after a 10-min rest between E1 and E2 (*top*), as evidenced by the smaller curvature of de2. They exhibited an even greater reduction in direct effect size in E4 compared with E3 after exercise (*bottom*). *Middle* and *right*: hand paths for the NF (*middle*) and FR (*right*) protocols in the first and second retention tests.

Subjects Formed and Retained an Internal Model of the Force Field Before Fatigue

As expected, subjects adapted to the force field before being fatigued. They exhibited a significant direct effect when the field was unexpectedly applied ($P < 0.001$, *t*-test of direct effect magnitude in E1 compared with zero; Figs. 3–5) but then improved their reaching performance ($P < .001$, *t*-test of performance improvement in E1 compared with zero; Fig. 6*A*). They also exhibited aftereffects when the force field was unexpectedly removed ($P < .001$, *t*-test of aftereffect magnitude in *null 2* compared with zero; Fig. 6*D*), indicating that they had formed an internal model of the field.

Subjects also demonstrated retention of their internal model following the 10-min rest between E1 and E2 of the force field. The magnitude for E2 direct effect was significantly smaller
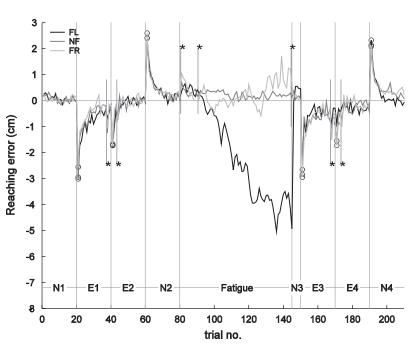
than that of E1 direct effect for each exercise protocol ($P < .001$, mixed model ANOVA with planned comparison of E1 and E2 direct effects across protocols, with follow-up paired *t*-tests for each exercise protocol; Fig. 5). The percentage reduction between E2 and E1 direct effect was $32 \pm 37\%$ (mean $\pm$ SD) for the FL protocol and $28 \pm 30\%$ for the FR protocol.

Movement Quality and Strength Decreased during Fatiguing Exercise

Following the first retention test of the experiment, subject's reached in the null field (*null 2*) to wash out the learned internal model. They then reached repeatedly while elastic bands pulled their arm to the left (FL) or right (FR) or with no elastic bands (NF). Movement smoothness and straightness degraded imme-

Fig. 4. Group averaged reaching error for the FR, FL, and NF protocols. In the FL and FR protocols, subjects were fatigued during the "fatigue" stage until they could no longer reach the target. Data for individual subjects in this stage were scaled across reaches so that they filled the 81- to 145-trial range. Subjects exhibited adaptive ability in each of the 4 force field exposure blocks (E1–E4), as evidenced by reduction of reaching error with practice and aftereffects after unexpected removal of the field (measured only after E2 and E4). Asterisks with short vertical lines indicate where strength evaluations were done.
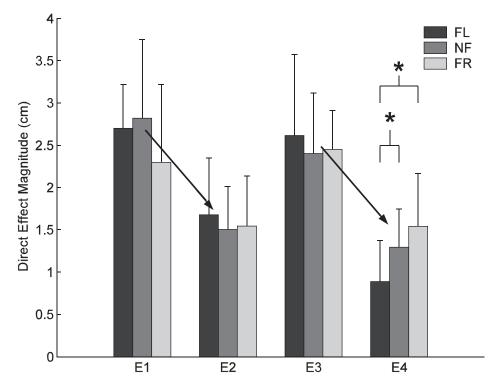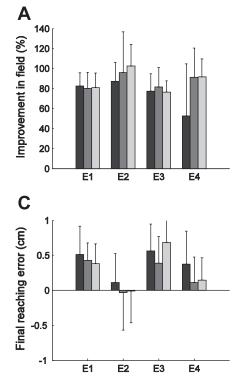
Fig. 5. Direct effect magnitudes. Subjects partially retained an internal model of the force field between E1 and E2, as well as between E3 and E4, as evidenced by the significantly reduced direct effect sizes in E2 and E4 ($P < 0.001$, paired t-test for each exercise protocol, significant drop denote by arrows). Subjects exhibited a significantly greater reduction in direct effect size in E4 after the FL protocol ($*P < 0.005$, Tukey's post hoc test after 1-way ANOVA comparing difference between direct effect size in E2 and E4, with exercise protocol as the independent variable). Bars show means ± SD across subjects.

diately when the elastic bands were attached and then further degraded with exercise (Fig. 7). Velocity peak count, velocity peak rate, and normalized path length increased significantly from baseline (evaluated over *trials 11–20*) on the first reach for which the elastic bands were attached ($P < 0.001$, paired *t*-test of measure in *trial 81* compared with mean over *trials 11–20*). Normalized path length and velocity peak count increased significantly between the start and end of the fatiguing field ($P < 0.002$, paired *t*-test of measure in first trial of fatiguing field compared with mean of measure across last five trials of fatiguing field), but velocity peak rate did not ($P = 0.25$), suggesting that the increase in number of velocity peaks was due mainly to an increase in total movement time. On removal of the elastic bands, velocity peak count, velocity peak rate, and normalized path length dropped substantially toward their normative values but were still significantly higher than at
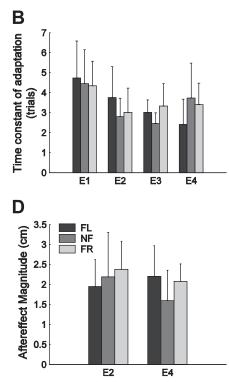

Fig. 6. Measures of motor adaptation during the 4 exposures to the force field (E1, E2, E3, E4). *A*: improvement in the field was defined as the % reduction in direct effect size following adaptation. *B*: time constant of adaptation was the number of reaches required for the smoothed trial series of reaching error to drop by 63%. *C*: "final error" was quantified as the mean reaching error in the last 5 trials during exposure to the field. *D*: aftereffects were measured following E2 and E4. There were no significant differences in these measures between the 3 exercise protocols (FL, NF, FR).
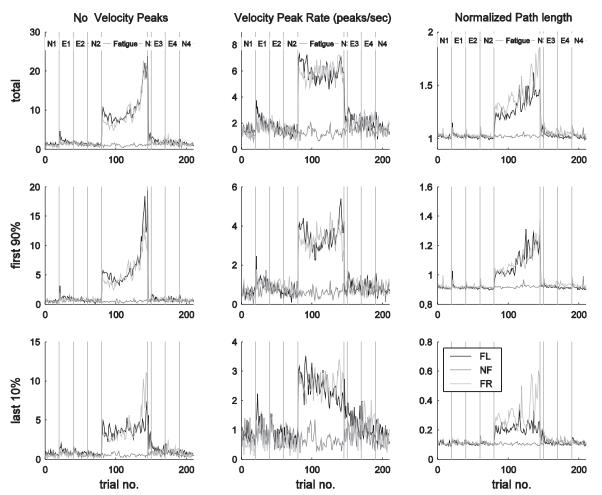
Fig. 7. Movement quality before, during, and after the FL, NF, and FR exercise protocols. Movement quality was quantified by the number of velocity peaks in the speed profile (*left*), the velocity peak rate, which is the number of peaks divided by the reach time (*middle*), and the path length normalized to a straight line (*right*). These measures are shown for the entire movement (*top*), the first 90% of the reach (*middle*), and the last 10% of the reach (*bottom*).

baseline for velocity peak rate ($P < 0.001$, paired *t*-test of measure in *null 3* compared with that in *trials 11–20*). The relative changes in these measures were similar for both the first 90% and last 10% of movement during and after exercise (Fig. 7), indicating that they were not due only to a decreased ability to touch the reaching target due to tremor in the last 10% of movement.

After the fatiguing exercise, subject strength in the left/right direction was $80 \pm 6\%$ of their starting strength for the FL protocol and $74 \pm 9\%$ for the FR protocol, which were significant reductions ($P < 0.001$, mixed-model ANOVA with planned comparison). In this weakened state, subjects then readapted to the force field (E3). Subject strength partially returned during adaptation in E3 (to $88 \pm 5\%$ of baseline for FL; $87 \pm 10\%$ for FR). Although this was a significant increase in strength compared with the end of the fatiguing field ($P < 0.001$, mixed-model ANOVA with planned comparison), strength was still significantly smaller than baseline strength levels ($P < 0.001$). The 10-min rest after E3 allowed more recovery, as their strength levels rose to $94 \pm 4\%$ of baseline for the FL protocol and $96 \pm 8\%$ for FR protocol, again a significant change compared with before rest ($P < 0.001$, mixed-model ANOVA with planned comparison) but still significantly less than baseline ($P < 0.001$).

Fatigue Did Not Substantially Affect the Ability of the Subjects to Adapt to the Force Field

After the exercise protocols, subjects again adapted to the force field (E3). Adaptation ability was quantified by the improvement in trajectory error during adaptation, the time constant of adaptation, the final trajectory error in the force field, and the aftereffect magnitude following unexpected removal of the field (Fig. 6). Two of these measures depended on the field exposure number within a given exercise protocol: there was a significant decrease in time constant of adaptation during the second, third, and fourth exposures to the force field, relative to the first ($P < 0.001$, repeated measures multivariate ANOVA with planned comparison), and final error was decreased marginally significantly in the E2 and E4 relative to the E1 and E3, respectively ($P = 0.055$, repeated-measures multivariate ANOVA with planned comparison). However, none of these measures depended significantly on the fatiguing exercise protocol.

Recovery Affected Retention

After adaptation, subjects repeated the retention test (E3, followed by 10 min of rest, then E4). The magnitude for E2 direct effect was significantly smaller than that of E1 direct

effect for each exercise protocol ($P < 0.001$, mixed-model ANOVA with planned comparison of E1 and E2 direct effects across protocols, with follow-up t-tests for each exercise protocol; Fig. 5). The percentage reduction between the direct effect in E3 and the direct effect in E4 was increased to $67 \pm 40\%$ for the FL protocol, whereas it was approximately the same as the first fatigue test for the other exercise protocols ($38 \pm 26\%$ for the FR protocol and $40 \pm 28\%$ for the NF protocol). This greater reduction in direct effect size after the FL protocol caused a significant statistical dependence of retention on exercise protocol ($P < 0.001$, one-way ANOVA, comparing difference between direct effect size in E2 and E4, with exercise protocol as the independent variable). Post hoc analysis revealed a significant linear contrast of direct effect size in E4 as a function of exercise protocol and significant differences between aftereffect size for the FL and NF, and FR and NF exercise protocols ($P < 0.005$, Tukey's test).

DISCUSSION

These results demonstrate that the motor system is able to form an internal model of a novel dynamic environment even when the muscles used to compensate for the environment are substantially fatigued. However, fatigue recovery affects the recall of the internal model. We first discuss a possible limitation of this study, then implications of the results for internal model construction and calibration, and then possible functional consequences.

A possible limitation of this study is that the order of exposure to the three exercise protocols (FL, NF, FR) was not randomized. Subjects performed the FL protocol before the NF protocol so that the number of reaches in the NF protocol could be matched to the number of reaches required for fatigue in the FL protocol. The FR protocol was added later as a control condition to distinguish a possible effect of generalized exercise from that of fatigue of specific muscles. The resulting sequential ordering of the protocols might be expected to produce increasingly better motor performance and retention with each protocol. However, the apparent retention in E4 was the best for the FL protocol, the first protocol experienced (Fig. 5). Thus the exercise protocol experienced had a stronger effect on retention than the protocol ordering. Furthermore, the direct effect sizes and time constants of adaptation were similar for each field exposure (E1, E2, E3, E4) for the three protocols (Figs. 4 and 5). Thus subjects experienced each protocol as essentially a novel environment. A likely cause for the lack of retention across experimental protocols was that we exposed subjects to the null field at the beginning and end of each protocol, which washed out any internal model. Practice in the null field abolishes previous learning of force fields (7).

Fatigue Did Not Substantially Affect Motor Adaptation to the Force Field

Subjects showed robustness to fatigue, adapting to the force field with a rate and accuracy that was comparable to that achieved when not fatigued. They also formed a similar internal model when fatigued, as quantified by the aftereffect size following adaptation. It is well known that fatiguing exercise slows muscle and increases the amount of muscle activation needed to generate a given force (e.g., Refs. 2, 8, 18, 24, 26, 45, 63, 64). The results of the present study indicate that the motor system compensates for such fatigue-related changes well enough not only to maintain movement accuracy but also to form accurate internal models, even when the muscles used by the internal model are fatigued

Motor control changes that maintain motor performance during fatigue have been observed previously. Fast wrist movements performed following fatigue showed early and prolonged electromyographic (EMG) patterns, even though the kinematics of movement are similar to those before fatigue (44). During a fast elbow flexion task, the motor system compensated for fatigue-related force reductions by prolonging the EMG agonist burst (i.e., acceleration) and delaying the EMG antagonist burst (i.e., braking) (10). Muscle activity timing also changed to preserve kinematics of rapid finger oscillations following fatiguing exercise (27). Large changes in the isometric torque-EMG relationship at the elbow following fatiguing exercise were accompanied by only small changes in joint stiffness, apparently because of a large increase in reflex gains (36). Fatigue compensation may also be evident in increased cortical activation, presumably to compensate for losses in muscle strength (42).

Internal model formation is an adaptive process that may itself be involved in compensating for muscle fatigue. Internal model formation is well described by a computational learning process that adjusts the previous motor command based on the most recent trajectory error (13, 14, 41, 62). When fatigue alters neuromuscular properties, the same motor command will not produce the same reaching trajectory. According to error-based learning models of internal model formation, the motor system will sense the trajectory error and incrementally adjust the motor command until it reduces the trajectory error. Thus it is conceivable that some of the changes in muscle activation that have been identified previously result because the motor system applies the same computational processes that it uses to compensate for external force fields. In other words, if the motor system uses trajectory error to drive adaptation, then it likely summates the trajectory errors induced by changes in the internal and external dynamic environments and responds to them in total.

Finally, motor adaptation performance may not have been altered substantially following fatigue because the exercise protocol fatigued motor units that were different than the ones used to adapt to the force field. The fatiguing exercise protocol used here required large forces (~ 70 N) relative to the force field protocol (~ 3 N). However, there was a statistically significant decrease in reaching smoothness following the exercise protocol, without the elastic bands attached, suggesting that fatigue at high forces did affect reaching performance at low forces. Furthermore, it seems very likely that that the motor units required to perform the force field task were fatigued because subjects exhibited a reduced direct effect in the second retention test in the FL condition. In other words, only when the muscles involved in resisting the force field were subjected to fatiguing exercise was retention following rest then altered, thus providing a causal link between the fatiguing exercise and the performance in the force field. We discuss the probable physiological mechanism of this finding next.

Recovery from Fatigue Altered the Recall of a Learned Internal Model

Subjects who were fatigued by pulling the arm to the left exhibited a greater reduction in initial trajectory error when they were reexposed to the force field, which also pushed the arm to the left. One possible explanation of this result is that exercise improved motor retention. Exercise is known to benefit cognitive function (11). However, when the subjects were fatigued by pulling the arm to the right with a comparable amount of exercise, they did not show the same reduction in direct effect size. Thus improved motor memory due to a generalized exercise effect is unlikely to explain the reduction in direct effect size.

A more likely explanation is that subjects overestimated the muscle activation required to cancel the force field, because their muscles recovered force-generating ability during rest. The FL exercise protocol fatigued the muscles that were needed to compensate for the force field (i.e., the muscles that pull the arm to the right). It is well established that fatigue increases the effort and neural activation required to produce a given force (e.g., Refs. 8, 24, 26, 31, 63). If the motor system remembered the previously needed level of activation during the second exposure to the force field, then the direct effect size would be decreased, since this level of activation would now produce more muscle force. The FR protocol did not have the same effect because it did not fatigue the muscles used to counteract the force field.

This effort-matching explanation is consistent with studies of isometric force estimation following fatiguing exercise (5, 6, 8, 21, 31, 32, 48, 52, 63). Several of these studies required subjects to match a force generated by one arm (the reference arm) with the other arm (the indicator arm) following fatiguing exercise of either arm. Subjects underestimated the force when the indicator arm was exercised and overestimated the force when the reference arm was exercised. A simple explanation for this finding is that the subjects used a signal related to the perceived effort as the cue for matching rather than the actual level of force itself. Scaling the generated force by the maximal force that could be generated produced a better match to the reference force, consistent with this explanation (8, 52). Force mismatches consistent with an effort match were also found when the angle of the reference arm was varied such that the same effort produced a different level of force because of the force-length property of muscles (5, 63). Changes in central neural drive and muscle soreness may also contribute to impaired force matching (8, 48). However, the contributions of these factors seem to make the most sense within a framework that assumes that subjects match effort when asked to match force (8, 48).

The present study extends these previous studies from an experimental protocol involving conscious, real-time estimation of isometric force to one involving implicit, time-delayed recall of the dynamic force required to counteract a force field during movement. Effort matching appears to play a key role in using internal models to move in recurrently experienced dynamic environments, as well as in conscious perception of real-time force.

This finding also suggests that the internal coordinate that the motor system uses to represent the output of internal models is more akin to effort or muscle activation than muscle force. Thus we suggest that internal models are constructed by pairing a signal related to the motor command (perhaps an "efference copy") with a signal related to the sensed movement rather than by pairing a representation of the sensed force with the sensed movement. Current models of internal model formation typically assume that force is the stored variable (13, 41, 53, 62). Such an assumption is computationally equivalent in the absence of muscle fatigue, but inaccurate under conditions that alter the relationship between muscle activation and force.

Another implication of these findings is that the motor system appears to require limb movement to fully recalibrate an internal model that it has learned. Group III and IV afferents could serve as fatigue sensors because they are sensitive to metabolic changes and muscle damage following fatiguing exercise (19). Such fatigue sensors could drive an automatic recalibration of muscle activation without the need for experiencing movement errors. However, in the present study, the motor system required several movements to recalibrate its internal model following recovery from fatiguing exercise.

We note that the motor system also required recalibration following the NF protocol. This is because retention was only partial (~30% following the 10-min rest period examined here), even when the subjects did not perform fatiguing exercise. The finding of partial retention after a short rest suggests that internal models, or the recall processes associated with them, experience a sort of time-dependent decay. Movement-based recalibration may thus be a general process used by the motor system to handle a range of commonly experienced, dynamics-altering perturbations, including periods of rest and fatigue.

Effort, Rather than Fatigue Alone, Adversely Affected Movement Quality

A secondary result of this study was that effort had a more powerful influence on movement quality than fatigue itself. Movement smoothness and straightness decreased dramatically when subjects reached with the elastic bands attached to the wrist. When the elastic bands were removed, the subjects immediately improved their movement quality almost but not completely to baseline levels. This result indicates that movement smoothness was related primarily to effort of movement, rather than fatigue alone, since the arm muscles had roughly the same fatigue level on the first trial after removal of the band as before removal. Only a very short time period of 2–3 s separated these consecutive trials, so it seems reasonable that no substantial recovery could have occurred in such a short time period. This result is consistent with previous studies that have found a decrease in the smoothness of force with increasing effort during isometric force matching (15, 30, 33, 57, 58).

Practical Implications

The primary finding of this study is that an internal model learned during a fatigued state is not replayed in the same way as one learned when not fatigued. A likely explanation for this finding is that the motor system expresses the internal model as a mapping between the arm's kinematic state and a motor output variable related to effort or activation. This result has two practical implications for movement training and exercise.

First, this result suggests that persons may at first move in an uncoordinated way when they attempt to replicate a skill learned previously during intensive exercise because they have stored a representation of the activation required for the task rather than the force required. Second, this result suggests that internal models require a brief period of recalibration following rest and that this recalibration requires movement practice. In this framework, the benefits of warm-up exercise for improving motor performance and reducing injury likelihood may be understood partially as an error-based recalibration of an internal model.

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