Maximal instantaneous muscular power after prolonged bed rest in humans

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Ferretti, Guido, Hans E. Berg, Alberto E. Minetti, Christian Moia, Susanna Rampichini, and Marco V. Narici. Maximal instantaneous muscular power after prolonged bed rest in humans. J Appl Physiol 90: 431–435, 2001.—A reduction in lower limb cross-sectional area (CSA) occurs after bed rest (BR). This should lead to an equivalent reduction in maximal instantaneous muscular power ($W_p$) if the body segments’ lengths remain unchanged. $W_p$ was determined during maximal jumps off both feet on a force platform before and on days 2, 6, 10, 32, and 48 after a 42-day duration BR. CSA of thigh muscles was measured by magnetic resonance imaging before and on day 48 after BR. Before BR, $W_p$ was 3.63 ± 0.43 kW or 48.6 ± 3.3 W/kg. On days 2 and 6 after BR, $W_p$ was reduced by 23.7 ± 6.9 and 22.7 ± 5.4% ($P < 0.01$), respectively. Thigh extensors CSA ($CSA_{EXT}$) was 16.7 ± 4.7% ($P < 0.01$) lower than before. When normalized per $CSA_{EXT}$, $W_p$ was reduced by only 4.8 ± 4.5% ($P < 0.05$). By day 48 of recovery, $W_p$ had returned to baseline values. Therefore, if $W_p$ is appropriately normalized for CSA of the extensor muscles, the reduction in $CSA_{EXT}$ explains most of the decrease in $W_p$ decrease after BR. Other factors such as a deficit in neural activation or a decrease in fiber-specific tension may account for only 5% of the $W_p$ loss after BR.

The CSA of both thigh extensor and calf plantar flexor muscles is decreased by bed rest (BR) and spaceflight (6, 9, 24, 25, 29). This being the case, prolonged BR and spaceflight should result in a significant reductions of $W_p$. As no changes in segment length occur during BR, such a reduction should be proportional to that of CSA.

Contradictory with this hypothesis is the observation that, after prolonged spaceflight, the decrease in $W_p$ was remarkably greater than that in CSA (2). These authors attributed their results to impairment of motor control. However, in their study, total thigh muscle CSA, rather than knee extensors CSA, was measured. As a result of this approach, these authors might have underestimated the CSA decrease of the active muscle mass and thus overestimated the decrease in $W_p$ per unit of CSA because 1) only the chain of extensor muscles, mainly of the thigh, is active during the push phase of the jump and 2) the decrease in CSA may be heterogeneously distributed among the various muscles, being predominant in the extensors (24, 25).

To our knowledge, the literature contains no $W_p$ data taken after prolonged BR. Thus we carried out the present study, which was aimed at determining the changes in $W_p$ after prolonged BR and correlating the changes in $W_p$ with the changes in the CSA of the lower limb extensor muscles, to ascertain whether changes in muscle size could entirely explain the expected drop of power.

METHODS

Study design. Seven healthy young men, who had previously given their written, informed consent, participated in this study. At the beginning of the study, mean age was 28 ± 1 (SD) yr, height was 1.76 ± 0.01 m, and body mass was 74.7 ± 8.8 kg. The study was approved by the local ethics committee (Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale, Toulouse I, France). All ex-

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The study consisted of three phases: 1) baseline control experiments before BR, including performance of magnetic resonance imaging (MRI) for CSA determination and W˙p measurements; 2) a 42-day, head-down tilt (−6°) BR period without countermeasures (no deviations from the lying position were permitted, and neither exercise nor muscle contraction tests were allowed during this period); and 3) final experiments after BR. These included W˙p measurements on days 2, 6, 10, 32, and 48 during recovery, and CSA measurements (by MRI) of the thigh muscles were carried out on day 5 of recovery.

Muscle CSA. CSA of the lower limb muscles were computed from transaxial images obtained by whole body MRI (Magnetom 63 SP 4000, Siemens, Germany). Images were obtained at three levels [3/10 (−2), 5/10 (0), and 7/10 (−2)] of the femur length, calculated from the femoral head to the upper edge of the patella. Slice thickness was 10 mm, repetition time was 700 ms, and echo time was 12 ms. Each film was digitally scanned (StudioScan II, Agfa) at a resolution of 150–185 dpi. The resulting files were then processed with NIH Image 1.52, a public domain image-processing program, on an Apple Duo 230 computer. Contours of each thigh muscle were individually drawn by hand. Total thigh CSA (CSATOT) was expressed as the sum of all muscle CSAs (extensors, flexors, and adductors). CSA of the extensors (CSAEXT) included the CSAs of the quadriceps heads.

Maximal W˙p. W˙p was determined during a maximal vertical jump off both feet on a force platform, as proposed by Davies and Rennie (11). We chose a squatting starting position, with an angle between the thigh and the calf of ~90°, to control the range of motion and to minimize the unavoidable negative work done by the lower limb muscles at the onset of the push. The time course of the changes of the vertical forces was monitored by eight strain gauges located at the four corners of the platform and acquired by a computer (ALR 486 DX 33) at a frequency of 100 Hz. Power (W) at time (t) was calculated as the product of vertical force (F) times the corresponding vertical velocity of the center of gravity (v)

\[
W(t) = F(t) \times v(t) \tag{1}
\]

where

\[
F = m(g + a) \tag{2}
\]

with \(m\) being the subject’s mass, \(g\) the acceleration of gravity, and \(a\) the vertical acceleration imposed by muscle contraction to the center of gravity. The \(a\) at every time instant was computed from the force measurements by means of Eq. 2. Then \(v\) was calculated as the time integral of \(a\) during the push phase of the jump. The maximal calculated value of \(W(t)\) was retained as the \(W_p\) developed during the jump (16).

The average power (\(W_p\)) during the whole push phase of the jump was also determined as the integral mean of the time course of power during the push.

The correctness of the starting position was checked by determining the negative work performed before the push phase of the jump as the time integral of the flexion phase (negative velocity) of the power vs. time curve. Only jumps in which negative work was <10 J were retained.

Statistics. Data are given as means ± SD. One-way ANOVA for repeated measurements was used to test the significance of the \(W_p\) changes as a function of time. Significant interactions were then located by a post hoc (Bonferroni) test. Student’s t-test for paired observations was used to test the significance of the CSA changes observed after BR. The level of significance was set at \(P < 0.05\). Linear regressions were calculated by means of the least squares method.

RESULTS

\(W_p\) and \(W_a\) data are summarized in Table 1. On day 2 after BR, absolute and specific \(W_p\) were 23.7 ± 6.9 and 22.7 ± 5.4% less than before BR (\(P < 0.05\)). Similarly, \(W_p\) was 20.5 ± 11.0% lower at the end of BR than before (\(P < 0.05\)). On day 6 of recovery, when the closest power determination to the CSA measurement after BR was obtained, \(W_p\) was 20.9 ± 3.4 and 20.2 ± 1.6% less than before BR (\(P < 0.05\)). The observed decrease in either \(W_p\) or \(W_a\) after BR results from a drop of both the maximal velocity attained during the jump (−12.7±4.6 and −11.7±2.5% on days 2 and 6 after BR, respectively; \(P < 0.05\) for both cases) and the maximal contraction force during the jump (−14.7±5.5 and −11.8±5.2% on days 2 and 6 after BR, respectively; \(P < 0.05\) in both cases).

After bed rest, CSATOT was 12.2 ± 5.8% (\(P < 0.05\)) lower than before, whereas CSAEXT was 16.7 ± 4.7% lower than before, and the difference was significant (\(P < 0.01\), paired t-test). The latter decrease was evident in all subjects, ranging between 11.4 and 25.8% and covered most of the decrease in CSATOT.

\(W_p\) determined on recovery day 6, is plotted in Fig. 1 as a function of the CSATOT observed on recovery day 5. A significant linear relationship was found (\(y = 0.05x + 0.024; r = 0.904, P < 0.0001\)). When expressed per unit of CSATOT (Table 2), \(W_p\) after BR was 9.7 ± 5.2% lower (\(P < 0.05\)) than before BR because the decrease in \(W_p\) was greater than the corresponding decrease in CSATOT. However, when \(W_p\) was expressed per unit of CSAEXT, this decrease was much less (4.8 ± 4.5%) but still significant (\(P < 0.05\)). By analogy, \(W_a\), expressed per unit of CSAEXT, was 10.1 ± 9.2% lower than before BR (\(P < 0.05\)).

The kinetics of recovery of \(W_p\) is shown in Fig. 2. This figure is a semilogarithmic plot of the changes in \(W_p\) with respect to the values before BR, as a function of the time of recovery. The highly significant regression equation, \(y = −1.454 − 0.026x\) (\(n = 31; r = 0.84, P < 0.00001\)), is compatible with a simple exponential model of the \(W_p\) kinetics during recovery, with a cal-

Table 1. Effects of 42 days of bed rest on maximal instantaneous muscular power

<table>
<thead>
<tr>
<th>Pre</th>
<th>R+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>M(_p) kg</td>
<td>74.7 ± 8.8</td>
</tr>
<tr>
<td>W(_p) kW</td>
<td>3.63 ± 0.44</td>
</tr>
<tr>
<td>W(_p) W/kg</td>
<td>48.6 ± 3.2</td>
</tr>
<tr>
<td>W(_p) W/kg</td>
<td>21.5 ± 2.0</td>
</tr>
<tr>
<td>F, kN</td>
<td>1.56 ± 0.15</td>
</tr>
<tr>
<td>v, m/s</td>
<td>2.65 ± 0.06</td>
</tr>
</tbody>
</table>

Values are means ± SD; \(n = 7\). Pre, values observed before bed rest; R + 2, values observed on day 2 after bed rest; \(Mb\), body mass; \(W_p\), maximal instantaneous power; \(W_p\), maximal average power; F, maximal force; v, maximal velocity. Note that the reported force and velocity values are not those observed at \(W_p\), but at the maximum attained during the jump.
cuted half-time of the $W_p$ recovery of 26.3 days. At the end of the recovery period, $W_p$ was $3.49 \pm 0.44$ W or $46.3 \pm 4.4$ W/kg, i.e., only 3.8 and 4.7% less than in the control condition, respectively (nonsignificant).

**DISCUSSION**

In this study, for the first time, $W_p$ was determined after prolonged BR, and its changes were correlated with the changes in CSA of the lower limb extensor muscles. Its main new finding is that the decrease in thigh muscle CSA (and thus muscle mass) after BR explains most of the observed drop in $W_p$ and that its more prevalent occurrence in the extensor than in the flexor muscle groups explains most of the discrepancy between the change in $W_p$ and that in CSA TOT.

After BR, the size of the CSA TOT reduction corresponded to the predictions that can be made from data in the literature (6, 9, 24, 25, 29). This decrease, however, is unevenly distributed, as it is larger in the extensor than in the other thigh muscle groups. This is in line with the observation that muscle hypotrophy preferentially affects the postural muscles of the lower limbs (24, 25). In addition, our subjects displayed structural and functional changes in the fibers of the vastus lateralis (1, 15, 23) but not in the deltoid muscle (12). The ensemble of these findings support the concept that gravity withdrawal specifically affects body supporting muscles.

The $W_p$ observed before BR were similar to those reported by others on men of similar ages and training conditions (8, 10, 19, 31). Besides the active muscle mass and CSA, $W_p$ and $W_a$ are known to depend on the muscle fiber type composition, the muscle ATP concentration, and either the rate of myosin ATP splitting (for $W_p$) or ATP resynthesis through the Lohmann reaction (for $W_a$) (16, 18, 19, 27, 28). The ATP splitting rate is affected, among others, by the type of myosin heavy chain that is expressed in a muscle fiber (7, 22) and, therefore, by the types of muscle fibers that are present in a given muscle. Muscle fiber composition, anaerobic enzyme activities, and myosin heavy chain composition in our subjects were the same at the end of the BR as before (15, 23) and, therefore, can be ruled out as determinants of the observed $W_p$ and $W_a$ drops.

On this basis, for an equal length of the body segments, it appeared reasonable to assume that the reduction in $W_p$ and $W_a$ after BR would be proportional to that in CSA, so that the specific power would remain unchanged. The decrease in CSA after BR was indeed associated with a drop in $W_p$ and a linear relationship between $W_p$ and CSA was observed, but, in contrast with this assumption, the decrease in $W_p$ was larger than that in CSA TOT, thus reducing the $W_p$ per unit of CSA TOT. However, when $W_p$ was related to CSA EXT instead of CSA TOT, its decrease was smaller but still significant. This indicates that most of the discrepancy between the decreases in CSA TOT and in $W_p$ was due to the fact that the CSA changes occurred in the active muscle mass.

By analogy, such a discrepancy also exists regarding the maximal isometric force ($F_{max}$) developed during
voluntary contractions, even though there is no direct relationship between force and $W_p$. Although it is known to be proportional to muscle CSA, $F_{max}$ is decreased after BR and/or lower limb unloading of varying duration by a greater extent than CSA (3, 4, 14, 20, 26). Berg et al. (4) determined $F_{max}$ in the same subjects that we used in the present study. We normalized their values to the present CSA\text{TOT} and found that, after BR, normalized $F_{max}$ decreased from 4.25 to 3.80 N/cm$^2$, being 10.8% lower than before BR.

The present results are similar to those obtained by others on cosmonauts after prolonged spaceflight (2). Both studies discovered a decrease in CSA\text{TOT} and $W_p$. Antonutto et al. (2) attribute this discrepancy to motor control alterations and maintain that, in BR, as opposed to spaceflight, muscles are still subjected to gravitational force, although they do not perform antigravitational work. Consequently, they consider gravity-desensitization after prolonged spaceflight as a plausible explanation for their findings. Those authors, however, could measure only CSA\text{TOT}. If, in the case of spaceflight, the reduction in CSA\text{TOT} is also due to a decrease in CSA\text{EXT}, as in the present study after BR, most of the $W_p$ changes observed by Antonutto et al. (2) would be a consequence of CSA\text{EXT} reduction instead of motor control impairment. Although its role is probably less than proposed, the hypothesis of motor control alterations cannot be fully rejected on the basis of the present results. In fact, several observations support this hypothesis. The cosmonauts studied by Antonutto et al. (2) underwent a physical countermeasure program, which might have reduced the degree of muscle hypotrophy after the flight with respect to that found after BR without countermeasures. Furthermore, in the cosmonaut, who endured a spaceflight duration comparable to that of the present BR, $W_p$ decreased more than in the subject who showed the greatest $W_p$ drop after BR. Moreover, an alteration in motor control is consistent with the greater motor unit activation at any given force level observed during submaximal voluntary isometric contractions after unloading (4, 5, 13, 26). Last but not least, Koryak (21) found a greater decrease in maximal voluntary isometric force than in maximal electrically-evoked tetanic contraction force after 1 wk of simulated spaceflight and attributed his findings to a deficit of neural activation. Indeed, an alteration in motor control may justify the small, but significant, unexplained fraction of change in $W_p$ after BR.

In the interpretation of the $W_p$ changes after BR, it should be kept in mind that only the CSA of thigh extensor muscles was measured, whereas the entire chain of antigravitational muscles is activated during the jump. Calf muscles are activated only in the final phase of a jump and thus are likely to contribute very little to the development of $W_p$. Yet this may not be the case for the hip extensor muscles. This interpretation implies the assumption that the CSA changes of these muscles and those of the thigh extensors are the same. Supporting this assumption would require determination of the CSA of the hip extensor muscles, which, to our knowledge, was never carried out after BR.

Assuming a monoeponential process, the kinetics of recovery of $W_p$ after BR shows that a complete recovery can be attained within 1.5 mo of reambulation in the absence of a specific training program. The power gain is greater in the earlier phase of recovery. The present subjects did not perform power training after reambulation, although its performance would have probably increased the speed of power recovery. It is noteworthy, however, that several of the structural and functional changes observed at the end of BR concerned indexes of aerobic performance (15, 30) and that this type of training would have interfered and eventually delayed recovery.

In conclusion, gravity withdrawal determines a specific hypotrophy of the extensor muscles of the thigh. This is the main cause for the drop in $W_p$ after BR, as it explains up to 79% of the observed changes. Other factors, such as alterations in motor control, changes in muscle architecture, reduction in fiber-specific tension, and, eventually, muscle damage, play a minor role at most, contributing collectively ≤21% of the observed drop in $W_p$ after BR.

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REFERENCES


