The Relationship between Muscle Weakness and Activation of the Cerebral Cortex Early after Unicompartmental Knee Arthroplasty

SHIN MORITA, PT¹⁾, TAKASHI KUSAKA, MD, PhD²⁾, SHOUICHI TANAKA, PT¹⁾,
EIJI YAMADA, PT, PhD³⁾, NOBUO ARIMA, MD, PhD⁴⁾, SUSUMU ITOH, MD, PhD⁵⁾,
TETSUJI YAMAMOTO, MD, PhD⁴⁾

¹⁾ Department of Rehabilitation, Faculty of Medicine, Kagawa University Hospital: 1750-1 Ikenobe, Miki-cho, Kita-gun, Kagawa 761-0793, Japan. TEL: +81 87-891-2306, FAX: +81 87-891-2307, E-mail: morishin@med.kagawa-u.ac.jp

²⁾ Maternal Perinatal Center, Faculty of Medicine, Kagawa University

³⁾ Department of Physical Therapy, Faculty of Health and Welfare, Tokushima Bunri University

⁴⁾ Department of Orthopedic Surgery, Faculty of Medicine, Kagawa University

⁵⁾ Department of Pediatrics, Faculty of Medicine, Kagawa University

Abstract. [Purpose] This study investigated the relationship between muscle weakness and activation of the cerebral cortex in the early period after unicompartmental knee arthroplasty (UKA). [Subjects] The subjects were 11 patients who underwent UKA. [Methods] They performed maximum isometric knee extension using a muscle force measurement device before, and 1 and 2 weeks after UKA. They were simultaneously measured for changes in the concentrations of oxyhemoglobin, deoxyhemoglobin, and total hemoglobin in the bilateral sensorimotor leg areas using functional multi-channel near-infrared spectroscopy. [Results] The muscle force decreased after UKA, and the active region of the sensorimotor leg area also narrowed. The severity of knee pain with muscle contraction 2 weeks after UKA did not change significantly compared with the preoperative level. [Conclusions] The patients treated with UKA displayed early postoperative muscle weakness, and the bilateral sensorimotor areas that were activated during maximum isometric knee extension were narrowed, suggesting that early postoperative muscle weakness is influenced by the central nervous system.

Key words: Unicompartmental knee arthroplasty, Muscle weakness, Cerebral cortex

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INTRODUCTION

Unicompartmental knee arthroplasty (UKA) is indicated for osteoarthritis of the knee (knee OA) and femoral condylar necrosis localized in the medial or lateral condyle. As only the medial (lateral) joint is replaced with a prosthesis in UKA, it is less invasive than total knee arthroplasty (TKA), in which the whole degenerated knee joint is replaced with a prosthesis. UKA results in rapid recovery of the range of motion of the affected joint compared with TKA, and has been suggested to shorten the patient's hospital stay and improve their functional score¹⁾.

Changes in the strength of the quadriceps femoris muscle on the treated side during maximum isometric knee extension after UKA and TKA have been investigated by several studies, and postoperative muscle weakness was observed²⁻⁴⁾. The causes of muscle weakness after TKA include pain⁵⁾, joint injury⁶⁾, and arthrogenic muscle inhibition (AMI), in which quadriceps femoris muscle inhibition is induced by exudate and swelling-associated changes in the intra-articular pressure transmitted from the articular receptor via the spinal cord⁷⁻⁹⁾. In the acute

postoperative period, patients lose approximately half of their preoperative quadriceps strength in the first month after TKA^{4, 10)}. It was reported that muscle weakness early after surgery is mainly due to the failure of voluntary muscle activation, not due to pain¹¹⁾. The failure of voluntary muscle activation is due to a reduction in the maximal force output resulting from inability to recruit all of the muscle's motor units or to attain the maximal discharge rate from the motor units that are recruited¹²⁾. Some studies have also reported that postoperative muscle weakness is a result of central nervous system influence^{2, 4)}. Muscle output during voluntary physical movement is controlled by the nervous system. Due to improvements in imaging techniques, studies of human brain function during voluntary movement have recently been performed¹³⁻¹⁷⁾, and the relationship between muscle output and brain function has also been investigated¹⁸⁻²¹⁾. However, no studies have investigated the contribution of lesser cerebral activation to muscle weakness after UKA. An investigation of the relationship between muscle weakness and activation of the cerebral cortex during the early period after UKA would be useful for designing more effective rehabilitation programs after knee replacement, because

Table 1. Patients' characteristics

Patient	Sex	Age (years)	Body mass index (kg/m ²)	Disease	Operated side
1	Male	82	27.7	Femoral medial condylar necrosis	Left
2	Female	78	28.3	Knee OA	Left
3	Male	69	26.4	Knee OA	Left
4	Male	70	31.3	Knee OA	Right
5	Female	67	29.1	Knee OA	Right
6	Female	73	29.7	Knee OA	Right
7	Female	72	24.4	Knee OA	Right
8	Female	80	31.4	Knee OA	Right
9	Male	70	22.5	Knee OA	Right
10	Female	79	23.8	Knee OA	Left
11	Female	77	24.8	Knee OA	Right

Knee OA: osteoarthritis of the knee

only strength training is carried out for muscle hypertrophy at present.

Functional near-infrared spectroscopy (fNIRS) measures changes in the hemoglobin (Hb) level and nerve activity-coupled cerebral blood flow, which allows the state of brain activity to be examined^{22–24}. Various brain functions have been measured by fNIRS, and recently there has been explosive growth in optical imaging research focusing on the complex motor behaviors affecting health and disease, including studies of the cortical contribution to everyday tasks such as walking and running^{25, 26}, motor skill learning^{27, 28}, cortical hemodynamics associated with athletic motor performance^{29, 30}, and the cortical compensation associated with recovery from cerebrovascular accidents^{31, 32}.

Therefore, in this study, we investigated whether the central nervous system is involved in the muscle weakness experienced after surgery by examining the function of the cerebral cortex using fNIRS during voluntary movement of a replacement knee during the early postoperative period. The purpose of the present study was to examine whether: the change in cerebral cortex activation accounts for the greater loss of quadriceps strength; the worsening of knee pain compared with the preoperative level accounts for a large portion of the worsening of voluntary activation after UKA; and the scalp blood flow influences fNIRS values of the sensorimotor area.

SUBJECTS AND METHODS

Study 1: The subjects were 11 patients (4 males and 7 females; mean age $\pm$ standard deviation [SD]: 74.3 ± 5.1 years (67–82 years)) with a mean body mass index $\pm$ SD of 27.2 ± 3.0 kg/m² (22.5 – 31.4 kg/m²) who underwent UKA at Kagawa University Hospital (Table 1). Ten patients had osteoarthritis of the knee (knee OA) (left side in 3 and right side in 7), and one patient suffered from femoral medial condylar necrosis (left side). Informed consent to participate in the study was received from the subjects after the study's objective had been explained to them. The patients sat on the edge of a bed with their hip and knee joints at flexion angles of 90° and 70°, respectively, and

performed maximum isometric extension of their treated knee, and the muscle force generated during this exercise was measured. A task consisting of resting for 20 seconds and maximum isometric extension of the treated knee for 5 seconds, was consecutively repeated 3 times on the treated side with an additional 20 seconds of rest allowed after the last repetition (total duration: 95 seconds). The subjects also performed another task (rest) comprised of resting in the sitting position without maximum isometric extension for 95 seconds. The muscle force generated during maximum isometric knee extension was measured using a μ Tas F-1 device (ANIMA Co., Japan). This device contains a thin sensor applied to the measurement site and measures the isometric muscle force generated during an exercise. A belt holds the device in place. The strength of the force generated during isometric knee extension per kg body weight (kgf/kg) is calculated as the mean of 3 measurements. A visual analog scale (VAS) was used to quantify knee pain during testing. Patients showed in the pain level on a scale from 0 (mm) to 100 (mm) using a ruler, with 0 (mm) representing no pain and 100 (mm) representing the worst pain imaginable. The knee pain rating was assigned after 3 maximum isometric extensions. A 3-wavelength (780, 805, and 830 nm) fNIRS system (OMM-3000 NIRStation, Shimadzu Co., Japan) was utilized to measure changes (mM $\cdot$ cm) in the concentrations of oxyhemoglobin, deoxyhemoglobin, and total hemoglobin ([oxyHb], [deoxyHb], and [totalHb], respectively; [totalHb] = [oxyHb] + [deoxyHb]) in the cortex by applying the modified Beer-Lambert law to the acquired data. fNIRS data were collected at 10-Hz sampling intervals.

A probe holder that was specially designed for the probe arrangement employed in this study was attached to the subject's scalp, and 12 probes (6 light-emitting and 6 light-receiving fibers) were positioned according to the 1–17 measurement channel arrangement. The probes were arranged at an inter-optode distance of 3 cm around the sensorimotor leg area (95×60 mm) with the Cz position as specified in the international 10–20 system³³) used as the baseline (Fig. 1). We principally used changes in [oxyHb] as a marker of regional activation, since previous findings have shown that oxyHb is more sensitive to locomotion-related

Fig. 1. Schematics of optode locations. The numbers 1-17 represent fNIRS measurement channels: ● Light source fiber, ○ Detector fiber, ◎ Optode of laser Doppler.

activities than deoxyHb^{25, 34}). To smooth the obtained data, the device selects 9 measurement points and performs 3 repetitions. The fNIRS data obtained from channels 5 and 12 were regarded as representing the contralateral sensorimotor leg area, and the data obtained from channels 6 and 13 were considered to represent the ipsilateral sensorimotor leg area. Since the UKA-treated side varied among the patients, fNIRS channels 5, 6, 12, and 13 (Fig. 1) were assigned to the anterior and posterior contralateral and ipsilateral sensorimotor leg areas, respectively, relative to the treated side.

SPSS Statistics 18 was used for all statistical analyses. First, for all 11 subjects, the changes in [oxyHb] measured during the 3 repetitions of the task were averaged in each channel. A linear equation with a gradient of 0 passing through the mean of the 150 data points obtained in the 15-second resting period before motion was subtracted from the measurement data to correct for the baseline data. For the changes in [oxyHb] obtained during the task before UKA and 1 and 2 weeks after UKA, and assessment for the presence of changes in [oxyHb] with the passage of time, one-way repeated analysis of variance (ANOVA) was conducted. Posthoc analysis using Dunnett's correction was performed on the time series of changes in [oxyHb] levels at each location, to determine the time when [oxyHb] changed significantly from the start of the task.

Next, using data for each of the 3 repetition performed by all 11 subjects, a linear equation with a gradient of 0 passing through the mean of the 150 data points obtained in the 15-second resting period before motion was subtracted from the measurement data to correct for the baseline data in each channel. For all 11 subjects, the mean [oxyHb] values for the 2 seconds from 3 to 5 seconds after exercise initiation and that for the corresponding 2 seconds during the rest were determined for each channel during each of the 3 repetitions (3 values for each subject, a total of 33 values before and during the task), and comparisons of these values were

made before UKA and 1 and 2 weeks after UKA using the Wilcoxon signed-rank test, to determine when the activated region showed a significant increase over the mean [oxyHb] in each channel.

To evaluate the significance of the changes in muscle force generated during maximum isometric knee extension by the 11 subjects, the muscle forces measured before, and 1 and 2 weeks after surgery were examined using one-way repeated ANOVA and Tukey's posthoc method. The knee pain values during maximum isometric knee extension before, and 1 and 2 weeks after surgery of the 11 subjects were examined using one-way repeated ANOVA, and Tukey's posthoc method. The significance level was chosen as 5% for all tests.

Study 2: The fNIRS measures the changes in the concentration of hemoglobin in all vascular components present in the tissues (scalp, skull, and cerebral cortex) penetrated by near-infrared radiation. We examined the influence of scalp blood flow on fNIRS measurement of the sensorimotor area. The subjects were 7 healthy, right-handed adults with no nervous, bone, or joint disease (mean age $\pm$ SD: 29.2 ± 1.6 years; range: 27–31 years). Informed consent to participate in the study was received from the subjects after explaining its objective to them. The subjects sat on a muscle force measurement device, Cybex NORM 770 (Cybex Inc., Medway, MA, USA) and performed maximum isometric knee extension of the right knee with a knee joint flexion angle of about 70°. A motion set consisting of resting for 15 seconds, motion for 5 seconds, and resting for 15 seconds was consecutively repeated 3 times (75 seconds) for each task. The device used to measure the influence of scalp blood flow on fNIRS signals during maximum isometric knee extension was a laser Doppler rheometer, ALF21R (ADVANCE Co., Japan). This is a 1-channel rheometer which simultaneously displays and outputs 3 values detailing the blood flow dynamics: tissue blood flow (Flow), red blood cell component (Mass), and flow rate component (Velocity). The measurement site was the forehead scalp, and optic fibers were attached to the frontal region. The skin tissue blood flow (ml/min/100 g) was measured simultaneously with maximum isometric knee extension at a time constant of 0.1 seconds, and the values measured in the 3 sets of the task were averaged. A linear equation with a slope of 0 passing the mean of 150 data points in the 15-second resting period before the task motion was subtracted from the measurement data to correct for the baseline. As in study 1, using the fNIRS system, the 12 probes were attached to the subject's scalp (Fig. 1). In addition, we principally used changes in [oxyHb] as a marker of regional activation.

The fNIRS data obtained at channels 5 and 12 were regarded as those of the contralateral sensorimotor leg area, and the data obtained at channels 6 and 13 as those of the ipsilateral sensorimotor leg area. For each of the 7 subjects, the changes in [oxyHb] measured during the 3 repetitions of the task were averaged for each channel. A linear equation with a gradient of 0 passing through the mean of the 150 data points obtained in the 15-second resting period before the task was subtracted from the measurement data to correct for the baseline data. The time to reach the maximum value of

[oxyHb] in each channel and the skin tissue blood flow after task initiation were analyzed using the paired t-test.

RESULTS

Study 1: Figure 2 shows topographical image patterns of averages of the time courses of [oxyHb], [deoxyHb], and [totalHb] in the bilateral temporo-parietal region during maximum isometric extension at 1 week after UKA in patient 4. It shows that increments in [oxyHb] and [totalHb] occurred mainly in the bilateral posterior sensorimotor areas during the task. Figure 3 shows averages of changes in [oxyHb], [deoxyHb], and [totalHb] in the anterior and posterior contra- and ipsilateral sensorimotor leg areas during maximum isometric knee extension before, and 1 and 2 weeks after UKA in the same subject. Before UKA, [oxyHb] increased and [deoxyHb] decreased during the task in all areas. The [totalHb] increased during the task in the posterior contra- and ipsilateral sensorimotor leg areas, and it decreased during the task in the anterior contra- and ipsilateral sensorimotor leg areas. However, [oxyHb] and [totalHb] increased during the task in only the bilateral posterior sensorimotor areas, and [oxyHb] and [totalHb] decreased in the bilateral anterior sensorimotor areas at 1 and 2 weeks after UKA.

A summary of [oxyHb] detected during maximum isometric extension in the anterior and posterior contralateral and ipsilateral sensorimotor leg areas before, 1 week after, and 2 weeks after UKA is shown in Table 2. Before UKA, in all of the channels corresponding to the anterior and posterior contralateral and ipsilateral sensorimotor areas, [oxyHb] increased with time from 0 seconds (motion initiation). Compared to those at rest, the mean [oxyHb] for the 2 seconds of maximum isometric extension increased in all of the channels corresponding to the anterior and posterior contralateral and ipsilateral sensorimotor areas. At 1 week after UKA, [oxyHb] increased in the posterior contralateral and ipsilateral sensorimotor areas, but not in the anterior contralateral or ipsilateral sensorimotor area. In addition, the activated regions of the bilateral sensorimotor areas had narrowed compared to before UKA. At 2 weeks after UKA, the changes were similar to those observed at 1 week after UKA.

The muscle force (mean $\pm$ SD) generated during maximum isometric knee extension was 0.32 ± 0.16 (kgf/kg) before UKA and 0.16 ± 0.08 and 0.20 ± 0.07 (kgf/kg) at 1 and 2 weeks after UKA, i.e., the muscle force was reduced at 1 week ($p = 0.004$) and 2 weeks ($p = 0.032$) after, compared with before UKA. The knee pain (VAS) during maximum isometric knee extension was 9.3 ± 14.1 (mm) before UKA and 36.4 ± 24.3 (mm) and 24.2 ± 22.2 (mm) at 1 and 2 weeks after UKA, i.e., knee pain had increased at 1 week ($p = 0.012$) after, compared with before UKA; however, there was no significant difference between before and 2 weeks after UKA.

Study 2: Each of the 7 subjects showed patterns of mean changes in skin tissue blood flow in the scalp and [oxyHb] at channel 5 during maximum isometric knee extension (Fig. 4). The skin tissue blood flow and [oxyHb] simultaneously

increased after task initiation; however, [oxyHb] reached a peak value during the task, and the skin blood flow reached its peak value at the end of the task. The time required after the initiation of maximum isometric knee extension to reach the peak value was compared between [oxyHb] of each channel and the skin blood flow. The time required to reach the maximum value of skin blood flow was significantly longer than that of [oxyHb] (Table 3).

DISCUSSION

The muscle force generated during maximum isometric knee extension was significantly decreased at 1 and 2 weeks after UKA compared with that before surgery. Weakness of the quadriceps femoris muscle after UKA and TKA has previously been reported²⁻⁴), and it was suggested that muscle weakness occurs early after surgery. Stevens et al.⁷) suggested that, at a mean of 3.5 weeks after TKA, the quadriceps strength had decreased by 60%. More than half of the strength loss was explained by an increase in AMI, and pain during contraction accounted for less than 25% of the increase in AMI from before to after surgery. Perhonen et al.¹⁰) detected quadriceps atrophy of less than 5% at 3 weeks after TKA, while other studies found quadriceps atrophy of 16–21% in healthy adults due to disuse or immobilization over a similar period of time. Therefore, muscle atrophy is not considered to cause the muscle weakness experienced after UKA and TKA. Rather, surgery-associated muscle weakness has been suggested to be the cause, due to inhibition of the central nervous system, based on studies of the central activation ratio of the quadriceps femoris muscle following TKA^{2,3}). However, the changes in cerebral cortical activation have not previously been investigated.

Two weeks after UKA, the postoperative score for pain during isometric knee extension was not significantly different from the preoperative score, whereas muscle weakness had developed. Minzer et al.³) reported that knee pain with muscle contraction after TKA plays a small role in the reduction of muscle activation, and the muscle weakness is due to the failure of voluntary muscle activation.

In this study, the oxyHb levels in the bilateral sensorimotor areas increased before UKA, but the areas displaying increased oxyHb levels were narrowed at 1 and 2 weeks after UKA. Animal and human studies have suggested that changes in physical afferent information or motor output result in alterations in the neuroplasticity of the sensorimotor areas of nervous system^{35, 36}), and physical inactivity has also been found to induce muscle weakness³⁷⁻³⁹). Liepert et al.⁴⁰) showed that the anterior tibial muscle-controlling region in the primary motor area narrowed after plaster fixation of the ankle joint for complex fracture of the distal tibia or talus, suggesting an association between inactivity-induced muscle weakness and reduced primary motor area activation. The muscle force generated during maximum isometric knee extension decreased after UKA. We was assume that changes in the afferent information supplied by the knee joint were caused by surgical stress and inhibited the activation of the relevant sensorimotor area, thereby, narrowing the active regions in the bilateral sensorimotor

Fig. 2. Dynamic optographic image of [oxyHb], [deoxyHb], and [totalHb] in the bilateral parieto-temporal region of patient 4 during maximum isometric extension 1 week after UKA. Images were taken at 1-sec intervals from 0 to 5 sec after the start of the task.

Fig. 3. Example of the anterior and posterior contra- and ipsilateral sensorimotor leg areas showing the time-course of [oxyHb], [deoxyHb], and [totalHb] during maximum isometric knee extension before and 1 and 2 weeks after UKA in one subject (Patient 4). a) anterior contralateral sensorimotor areas; b) posterior contralateral sensorimotor areas; c) anterior ipsilateral sensorimotor areas; d) posterior ipsilateral sensorimotor areas. The arrow indicates the 5-second maximum isometric knee extension period. The red, blue, and green indicate [oxyHb], [deoxyHb], and [totalHb], respectively.

Table 2. [OxyHb] changes in sensorimotor leg cortical areas during isometric knee extension before and after UKA

	Contralateral			Ipsilateral		
	Area	oxyHb		Area	oxyHb	
		Mean maximum value (mM · cm)	Time (sec)		Mean maximum value (mM · cm)	Time (sec)
Before UKA	Anterior	0.014 ± 0.013 [†]	2.8–5.0*	Anterior	0.019 ± 0.021 [†]	3.0–5.0*
	Posterior	0.020 ± 0.020 [†]	2.6–5.0*	Posterior	0.019 ± 0.019 [†]	2.6–5.0*
1 week after UKA	Anterior	0.007 ± 0.017	n.s.	Anterior	0.013 ± 0.019	n.s.
	Posterior	0.015 ± 0.010 [†]	1.8–4.6*	Posterior	0.013 ± 0.011 [†]	2.0–4.4*
2 weeks after UKA	Anterior	0.012 ± 0.021	n.s.	Anterior	0.009 ± 0.012	n.s.
	Posterior	0.016 ± 0.024 [†]	3.4–5.0*	Posterior	0.012 ± 0.015 [†]	2.4–5.0*

* A significant increase in the oxyHb level was detected vs. the value at 0 seconds $p < 0.05$. [†] Mean oxyHb level for the 2 seconds of maximum isometric extension vs. mean oxyHb for the corresponding 2 seconds of rest, $p < 0.05$. n.s.: not significant

Fig. 4. The changes in skin tissue blood flow at the scalp and [oxyHb] at channel 5 on maximum isometric knee extension. The arrow indicates the 5-second maximum isometric knee extension period. The error bar indicates SD.

areas at 1 and 2 weeks after UKA.

Since light-emitting and -receiving fibers are directly applied to the scalp, fNIRS reflects oxygen metabolism and blood flow in tissues that can be penetrated by near-infrared radiation. Heartbeat, respiration, and blood pressure rhythm have been reported to influence fNIRS measurement^{41, 42}. Therefore, it is necessary to confirm the influence of scalp blood flow on fNIRS measurements. In fNIRS during treadmill walking at different speeds⁴³ and a perception task²⁴, the simultaneously measured scalp (forehead) blood flow increased during the task, but the variation and level of increase varied among subjects. In this study, during maximum isometric knee extension, the time required to reach the maximum value of skin tissue blood flow and [oxyHb] of each of the individual channels were different. In addition, [oxyHb] in all of the sensorimotor areas during the task increased before UKA, but the increased areas narrowed after UKA. We suggest that the skin tissue blood flow is associated with changes in [oxyHb] measured by

Table 3. The time needed to reach the maximum value of [oxyHb] in each channel and the skin tissue blood flow during maximum isometric knee extension

	Time (s)
Skin tissue blood flow	5.1 ± 0.6
OxyHb of channel 5	3.7 ± 0.7*
OxyHb of channel 6	4.0 ± 0.6*
OxyHb of channel 12	4.1 ± 0.6*
OxyHb of channel 13	4.1 ± 0.6*

* Significant difference between the time points for the maximum oxyHb at each channel and skin tissue blood flow ($p < 0.05$)

fNIRS during maximum isometric knee extension; however, cerebral cortex activation can be assessed using the analysis of the time course of [oxyHb].

In rehabilitative muscle strength training, the muscle strength can be increased by motor imagery and mental practice^{44–46}, and it may prove to be a useful adjunct to traditional treatment options aimed at increasing the muscle strength⁴⁷. Mental training reportedly enhances the cortical output signal, which drives the muscles to a higher activation level and increases strength⁴⁸. The results of this study suggest that it is necessary to investigate the utility of muscle strength training that activates cerebral areas, such as motor imagery and mental practice, for early rehabilitation following knee arthroplasty.

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REFERENCES

- 1) Lombardi AV Jr, Berend KR, Walter CA, et al.: Is recovery faster for

- mobile-bearing unicompartmental than total knee arthroplasty? Clin Orthop Relat Res, 2009, 467: 1450–1457. [Medline] [CrossRef]
- 2) Mizner RL, Stevens JE, Snyder-Mackler L: Voluntary activation and decreased force production of the quadriceps femoris muscle after total knee arthroplasty. Phys Ther, 2003, 83: 359–365. [Medline]
 - 3) Mizner RL, Petterson SC, Snyder-Mackler L: Quadriceps strength and the time course of functional recovery after total knee arthroplasty. J Orthop Sports Phys Ther, 2005, 35: 424–436. [Medline]
 - 4) Stevens JE, Mizner RL, Snyder-Mackler L: Quadriceps strength and volitional activation before and after total knee arthroplasty for osteoarthritis. J Orthop Res, 2003, 21: 775–779. [Medline] [CrossRef]
 - 5) O'Reilly SC, Jones A, Muir KR, et al.: Quadriceps weakness in knee osteoarthritis: the effect on pain and disability. Ann Rheum Dis, 1998, 57: 588–594. [Medline] [CrossRef]
 - 6) Hurley MV: The effects of joint damage on muscle function, proprioception and rehabilitation. Man Ther, 1997, 2: 11–17. [Medline] [CrossRef]
 - 7) Fahrner H, Rentsch HU, Gerber NJ, et al.: Knee effusion and reflex inhibition of the quadriceps. A bar to effective retraining. J Bone Joint Surg Br, 1988, 70: 635–638. [Medline]
 - 8) Stokes M, Young A: The contribution of reflex inhibition to arithrogenous muscle weakness. Clin Sci, 1984, 67: 7–14. [Medline]
 - 9) McNair PJ, Marshall RN, Maguire K: Swelling of the knee joint: effects of exercise on quadriceps muscle strength. Arch Phys Med Rehabil, 1996, 77: 896–899. [Medline] [CrossRef]
 - 10) Perhonen M, Komi PV, Hakkinen K, et al.: Strength training and neuromuscular function in elderly people with total knee endoprosthesis. Scand J Med Sci Sports, 1992, 2: 234–243. [CrossRef]
 - 11) Mizner RL, Petterson SC, Stevens JE, et al.: Early quadriceps strength loss after total knee arthroplasty. The contributions of muscle atrophy and failure of voluntary muscle activation. J Bone Joint Surg Am, 2005, 87: 1047–1053. [Medline] [CrossRef]
 - 12) Kent-Braun JA, Le Blanc R: Quantitation of central activation failure during maximal voluntary contractions in humans. Muscle Nerve, 1996, 19: 861–869. [Medline] [CrossRef]
 - 13) Bandettini PA, Wong EC, Hinks RS, et al.: Time course EPI of human brain function during task activation. Magn Reson Med, 1992, 25: 390–397. [Medline] [CrossRef]
 - 14) Ehrsson HH, Fagergren A, Jonsson T, et al.: Cortical activity in precision-versus power-grip tasks: an fMRI study. J Neurophysiol, 2000, 83: 528–536. [Medline]
 - 15) Lui JZ, Dai TH., Siemionow V, et al.: Brain activation during muscle fatigue. Soc Neurosci Abstr, 1999, 25: 1915.
 - 16) Sanes JN, Donoghue JP: Plasticity and primary motor cortex. Annu Rev Neurosci, 2000, 23: 393–415. [Medline] [CrossRef]
 - 17) Yue GH, Liu JZ, Siemionow V, et al.: Brain activation during human finger extension and flexion movements. Brain Res, 2000, 856: 291–300. [Medline] [CrossRef]
 - 18) Dai TH, Liu JZ, Sahgal V, et al.: Relationship between muscle output and functional MRI-measured brain activation. Exp Brain Res, 2001, 140: 290–300. [Medline] [CrossRef]
 - 19) Dettmers C, Fink GR, Lemon RN, et al.: Relation between cerebral activity and force in the motor areas of the human brain. J Neurophysiol, 1995, 74: 802–815. [Medline]
 - 20) Thickbroom GW, Phillips BA, Morris I, et al.: Isometric force-related activity in sensorimotor cortex measured with functional MRI. Exp Brain Res, 1998, 121: 59–64. [Medline] [CrossRef]
 - 21) Johannsen P, Christensen LO, Sinkjaer T, et al.: Cerebral functional anatomy of voluntary contractions of ankle muscles in man. J Physiol, 2001, 535: 397–406. [Medline] [CrossRef]
 - 22) Hoshi Y, Tamura M: Detection of dynamic changes in cerebral oxygenation coupled to neuronal function during mental work in man. Neurosci Lett, 1993, 150: 5–8. [Medline] [CrossRef]
 - 23) Kato T, Kamei A, Takashima S, et al.: Human visual cortical function during photic stimulation monitoring by means of near-infrared spectroscopy. J Cereb Blood Flow Metab, 1993, 13: 516–520. [Medline] [CrossRef]
 - 24) Villringer A, Planck J, Hock C, et al.: Near infrared spectroscopy (NIRS): a new tool to study hemodynamic changes during activation of brain function in human adults. Neurosci Lett, 1993, 154: 101–104. [Medline] [CrossRef]
 - 25) Miyai I, Tanabe H, Sase I, et al.: Cortical mapping of gait in humans: a near-infrared spectroscopic topography study. Neuroimage, 2001, 14: 1186–1192. [Medline] [CrossRef]
 - 26) Miyai I, Yagura H, Oda I, et al.: Premotor cortex is involved in restoration of gait in stroke. Ann Neurol, 2002, 52: 188–194. [Medline] [CrossRef]
 - 27) Hatakenaka M, Miyai I, Mihara M, et al.: Frontal regions involved in learning of motor skill—a functional NIRS study. Neuroimage, 2007, 34: 109–116. [Medline] [CrossRef]
 - 28) Leff D, Orihuela-Espina F, Atallah L, et al.: Functional near infrared spectroscopy in novice and expert surgeons a manifold embedding approach. Lect Notes Comput Sci, 2007, 4792: 270–277. [CrossRef]
 - 29) Shibuya K, Tanaka J, Kuboyama N, et al.: Cerebral oxygenation during intermittent supramaximal exercise. Respir Physiol Neurobiol, 2004, 140: 165–172. [Medline] [CrossRef]
 - 30) Rupp T, Perrey S: Effect of severe hypoxia on prefrontal cortex and muscle oxygenation responses at rest and during exhaustive exercise. Adv Exp Med Biol, 2009, 645: 329–334. [Medline] [CrossRef]
 - 31) Miyai I, Yagura H, Hatakenaka M, et al.: Longitudinal optical imaging study for locomotor recovery after stroke. Stroke, 2003, 34: 2866–2870. [Medline] [CrossRef]
 - 32) Takeda K, Gomi Y, Imai I, et al.: Shift of motor activation areas during recovery from hemiparesis after cerebral infarction: a longitudinal study with near-infrared spectroscopy. Neurosci Res, 2007, 59: 136–144. [Medline] [CrossRef]
 - 33) Homan RW, Herman J, Purdy P: Cerebral location of international 10–20 system electrode placement. Electroencephalogr Clin Neurophysiol, 1987, 66: 376–382. [Medline] [CrossRef]
 - 34) Suzuki M, Miyai I, Ono T, et al.: Prefrontal and premotor cortices are involved in adapting walking and running speed on the treadmill: an optical imaging study. Neuroimage, 2004, 23: 1020–1026. [Medline] [CrossRef]
 - 35) Jones EG: Cortical and subcortical contributions to activity-dependent plasticity in primate somatosensory cortex. Annu Rev Neurosci, 2000, 23: 1–37. [Medline] [CrossRef]
 - 36) Sanes JN, Donoghue JP, Thangaraj V, et al.: Shared neural substrates controlling hand movements in human motor cortex. Science, 1995, 268: 1775–1777. [Medline] [CrossRef]
 - 37) Appell HJ: Skeletal muscle atrophy during immobilization. Int J Sports Med, 1986, 7: 1–5. [Medline] [CrossRef]
 - 38) Enoka RM: Neural adaptations with chronic physical activity. J Biomech, 1997, 30: 447–455. [Medline] [CrossRef]
 - 39) Lieber RL: Skeletal muscle adaptation to decreased use. Skeletal, muscle structure, function, & plasticity, the physiological basis of rehabilitation. Baltimore, Lippincott Williams & Wilkins, 2002, pp 225–286.
 - 40) Liepert J, Tegenthoff M, Malin JP: Changes of cortical motor area size during immobilization. Electroencephalogr Clin Neurophysiol, 1995, 97: 382–386. [Medline] [CrossRef]
 - 41) Boas DA, Dale AM, Franceschini MA: Diffuse optical imaging of brain activation: approaches to optimizing image sensitivity, resolution, and accuracy. Neuroimage, 2004, 23: S275–S288. [Medline] [CrossRef]
 - 42) Obrig H, Neufang M, Wenzel R, et al.: Spontaneous low frequency oscillations of cerebral hemodynamics and metabolism in human adults. Neuroimage, 2000, 12: 623–639. [Medline] [CrossRef]
 - 43) Kohno S, Miyai I, Seiyama A, et al.: Removal of the skin blood flow artifact in functional near-infrared spectroscopic imaging data through independent component analysis. J Biomed Opt, 2007, 12: 062111. [Medline] [CrossRef]
 - 44) Yue G, Cole KJ: Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. J Neurophysiol, 1992, 67: 1114–1123. [Medline]
 - 45) Jackson PL, Lafleur MF, Malouin F, et al.: Potential role of mental practice using motor imagery in neurologic rehabilitation. Arch Phys Med Rehabil, 2001, 82: 1133–1141. [Medline] [CrossRef]
 - 46) Zijdwind I, Toering ST, Bessem B, et al.: Effects of imagery motor training on torque production of ankle plantar flexor muscles. Muscle Nerve, 2003, 28: 168–173. [Medline] [CrossRef]
 - 47) Ranganathan VK, Siemionow V, Liu JZ, et al.: From mental power to muscle power—gaining strength by using the mind. Neuropsychologia, 2004, 42: 944–956. [Medline] [CrossRef]
 - 48) Sidaway B, Trzaska AR: Can mental practice increase ankle dorsiflexor torque? Phys Ther, 2005, 85: 1053–1060. [Medline]