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ORIGINAL RESEARCH

Noninvasively measuring the hemodynamic effects of massage on skeletal muscle: A novel hybrid near-infrared diffuse optical instrument

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Summary Increase in tissue blood flow is one of the most acknowledged potential effects of massage; however, actual research studies examining this phenomenon are inconsistent and inconclusive. One possible reason for continued uncertainty regarding this topic is methodology, specifically how tissue blood flow is measured because limitations exist in previously utilized technologies. Near-infrared spectroscopy (NIRS) affords massage researchers a versatile and non-invasive measurement option by providing dynamic information on oxy- and deoxy-hemoglobin concentrations, total hemoglobin concentration, and blood oxygen saturation in deep tissue. Near-infrared diffuse correlation spectroscopy (DCS) is an innovative technique for continuous non-invasive measurement of blood flow in deep tissue. The combination of these two technologies has resulted in a novel hybrid diffuse optical instrument for simultaneous measurement of limb muscle blood flow and oxygenation. The purposes of this short report are to review previous blood flow measurement techniques and limitations in massage therapy research, introduce a novel hybrid near-infrared diffuse optical instrument that addresses previous limitations in the assessment of hemodynamic properties, outline a proposed massage therapy pilot study utilizing the novel measurement technology, and present sample data from a pilot participant using the introduced novel technology.

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Statement of purpose

The overall intention of this short report is to introduce a novel optical technology for non-invasive assessment of tissue hemodynamic properties to the massage therapy (MT) community. This report will 1) review previous blood flow and MT research, specifically blood flow measurement techniques and their limitations; 2) introduce a novel hybrid near-infrared diffuse optical instrument to assess deep tissue hemodynamics to MT researchers that address previous limitations in measurement techniques; 3) outline a proposed MT pilot study using the hybrid optical instrument for monitoring of MT-induced changes in limb muscle hemodynamics; and, 4) present descriptive data from a pilot study participant.

Blood flow and massage therapy

One of the most touted and referred to effects of massage therapy (MT) is an increase in tissue blood flow (Fritz, 2004; Moyer et al., 2004; Weerapong et al., 2005). However, as Weerapong and colleagues point out in a review of massage mechanisms and effects on performance, muscle recovery and injury prevention, investigations of MT effects on tissue blood flow are inconsistent and inconclusive primarily due to design limitations such as small sample sizes, lack of control groups, and measurement limitations (Weerapong et al., 2005). Studies not included in the Weerapong review found massages from compressed air (Mars et al., 2005) and air cuffs (Tochikubo et al., 2006) to significantly increase skin blood flow and blood volume in the toes, respectively. Additionally, MT applied by a therapist has been found to increase cerebral blood flow (Buckle et al., 2008; Ouchi et al., 2006), lumbar paraspinal muscle blood volume (Mori et al., 2004), lumbar skin temperature (Mori et al., 2004; Sefton et al., 2010), and skin blood flow in the toes and upper leg (Castro-Sanchez et al., 2009; Hinds et al., 2004). Conversely, MT has not been found to have positive effects on deep quadriceps or forearm muscle blood flow in studies assessing their outcomes indirectly using Doppler ultrasound (Hinds et al., 2004; Shoemaker et al., 1997; Tiidus and Shoemaker, 1995; Wiltshire et al., 2010) and laser Doppler (Hinds et al., 2004) which further supports the assertion made by Weerapong et al that MT effects regarding muscle blood flow are conflicting.

Methodological issues, including how blood flow is measured, present possible reasons for the continued uncertainty regarding MT effects on muscle hemodynamic properties. Specifically, do measurement tools previously utilized in MT research appropriately assess tissue hemodynamic properties in muscles? In addition, many measurement techniques have sensitivity and/or accessibility issues that may hinder research endeavors. For example, past MT studies used measurement techniques such as venous occlusion plethysmograph and ^{133}Xenon wash-out technique (Hansen and Kristensen, 1973; Hovind and Nielsen, 1974). Unfortunately, these techniques can be cumbersome and have methodological issues that make real time measurement in relation to the massage procedure problematic (Sefton et al., 2010; Tiidus and Shoemaker, 1995). Many recent MT studies have employed Doppler ultrasound or laser Doppler technology (Agarwal et al., 2000; Hinds et al., 2004; Mars et al., 2005; Shoemaker et al., 1997; Tiidus and Shoemaker, 1995; Tochikubo et al., 2006; Wiltshire et al., 2010). However, laser Doppler can only measure blood flow at the skin level and Doppler ultrasound is not sensitive to blood flow in smaller vasculature (Yu et al., 2005a), such as the capillary beds. In fact, blood flow to an area of interest measured by Doppler ultrasound is determined by arterial size and blood velocity in macro-regions rather than in specific muscle tissue. Thus, blood flow in skeletal muscle is not actually measured but rather speculated using these measurement methods. Other MT studies utilized more involved measures such as positron emission tomography (PET) (Ouchi et al., 2006), single photon emission computed tomography (SPECT) (Buckle et al., 2008), and dynamic infrared thermography (Sefton et al., 2010) which due to large and costly instrumentation, may limit these measures accessibility to many investigators interested in conducting MT studies examining hemodynamics.

Novel hybrid near-infrared diffuse optical instrument

Near-infrared spectroscopy (NIRS) may be a more accessible measurement option for MT researchers and has a variety of research and clinical applications including versatility and non-invasive assessment of deep tissue optical properties (De Blasi et al., 1994; Ferrari et al., 1997; Mancini et al., 1994; Van Beekvelt et al., 2001; Wolf et al., 2003a).Specifically, NIRS provides dynamic information about oxy- and deoxy-hemoglobin concentrations, total hemoglobin concentration, and blood oxygen saturation in deep muscle tissue (Wolf et al., 2003b) and can be repeatedly used without risk or discomfort (Mancini et al., 1994). NIRS has been utilized in resent MT research as a way to indirectly examine blood flow following isometric lumbar exercise (Mori et al., 2004) and during prolonged driving (Durkin et al., 2006). However, while increased oxy- or total hemoglobin concentrations as measured by NIRS may *suggest* an increase in blood flow, this assessment is also only an indirect estimate of tissue blood flow.

Near-infrared diffuse correlation spectroscopy (DCS) is an emerging technique for continuous, non-invasive, and direct measurement of relative change in blood flow (rBF) in deep tissues (Cheung et al., 2001; Culver et al., 2003; Dietsche et al., 2007; Durduran et al., 2004,2009; Gagnon et al., 2008; Li et al., 2008; Sunar et al., 2006; Yu et al., 2005b,2006; Zhou et al., 2007,2009) including skeletal muscle (Shang et al., 2009,2010; Yu et al., 2005a,2007). DCS has been validated to measure rBF by other standards including Doppler ultrasound (Buckley et al., 2009), laser Doppler (Durduran, 2004), Xenon-CT (Kim et al., 2010), and arterial-spin-labeled MRI (Durduran et al., 2004; Yu et al., 2007). Assessment of rBF in addition to oxy- and deoxy-hemoglobin concentrations in deep skeletal muscle allows for an estimation of muscle oxygen metabolism (Yu et al., 2005a), thus having the potential to provide great insights into physiologic mechanisms and/or responses to MT.

A proposed study in the Graduate Center for Gerontology and Center for Biomedical Engineering at the University of

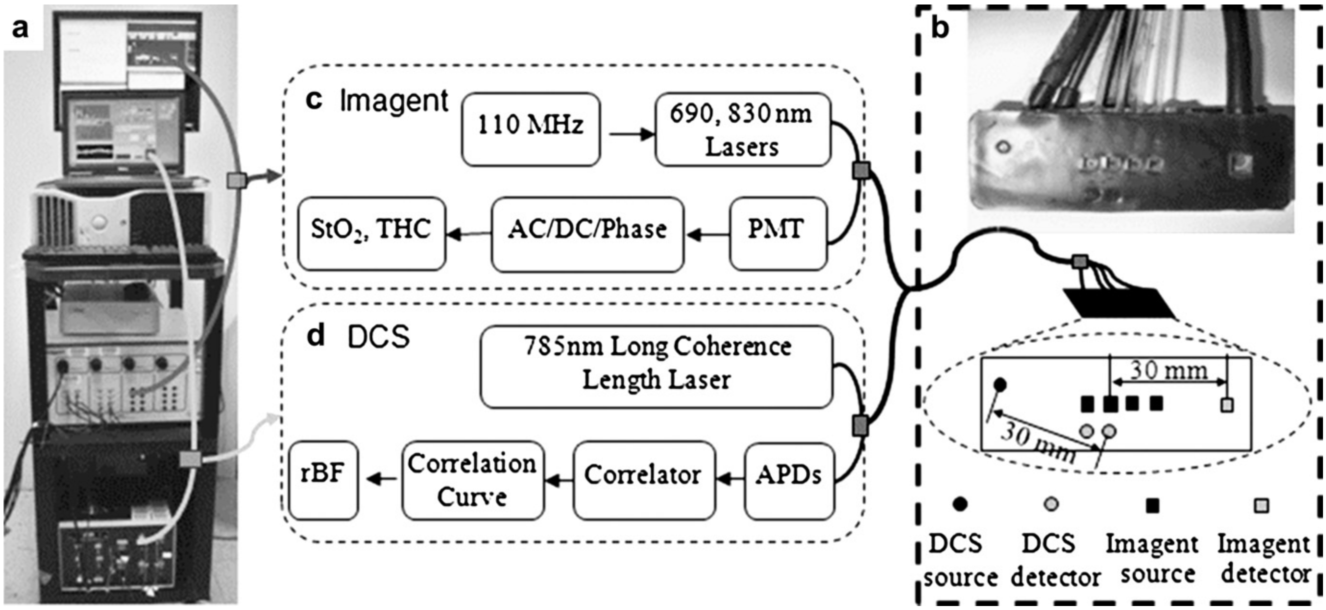

Figure 1 A hybrid diffuse optical instrument combining a commercial NIRS tissue oximeter (Imagent) for tissue oxygenation measurement with a custom-made diffuse correlation spectroscopy (DCS) for tissue blood flow measurement. (a) A photograph of the hybrid system. (b) A fiber-optic probe containing multiple source and detector fibers for Imagent/DCS. (c) A schematic of the Imagent. (d) A schematic of the DCS.

Kentucky (UK) will measure MT effects on skeletal muscle hemodynamics using a novel hybrid near-infrared diffuse optical instrument (Figure 1a) that combines a commercial NIRS (Imagent, ISS Inc., IL, USA) with a custom-made DCS for simultaneous measurement of muscle blood flow and oxygenation. The principal of this hybrid instrument has been described elsewhere (Shang et al., 2009). Briefly, near-infrared light is employed to probe tissue properties with optical fibers coupling light in and out of the tissue of interest (Figure 2). The photons emitted from the source fiber are scattered or absorbed by biological tissues and only some of them are collected by the detector fiber. Therefore, measurements of light intensity and its fluctuation throughout the tissue allow for the quantification of tissue optical properties (e.g., absorption, scattering, motion of moving red blood cells).

The distal terminals of these source and detector fibers are embedded in a foam pad (Figure 1b) that can be secured over the region of interest (e.g., leg, arm, back). The relatively slow changes of tissue optical properties (i.e., tissue absorption and scattering) are measured with a frequency-domain NIRS tissue oximeter (Imagent, Figure 1c) using modulated laser diodes at 690 and 830 nm and a photomultiplier (PMT) detector. The Imagent extracts the information of tissue absorption and scattering from the detected amplitude (AC/DC) and phase of transported light through

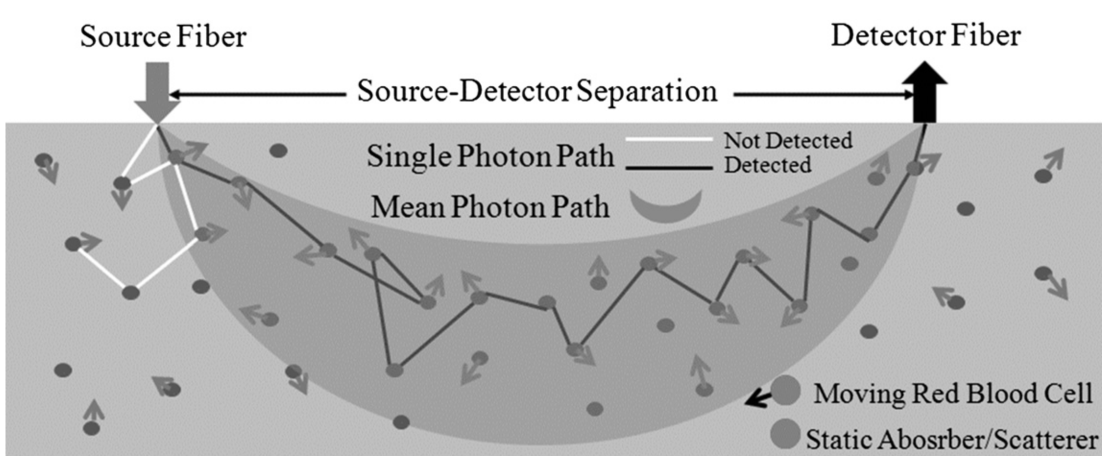

Figure 2 Light transport over long distances in tissues as a diffusive process. The photons emitted from the source fiber are scattered by static (e.g., organelles, mitochondria) and dynamic (e.g., moving red blood cells) scatterers or absorbed by absorbers (e.g., hemoglobins, water, lipids) and only some of them are collected by the detector fiber. The photons undergo scattering, absorption and experience Doppler shifts when they are scattered from the moving red blood cells. The solid line indicates a single photon path in tissue and the shaded "banana" shape represents the mean path of multiple detected photons.

Table 1 MT procedure description and timing (protocol is performed only on one leg).

Description	Duration	Time Elapsed	Time Remaining
Compression from top of knee through hip	30 s	0:30	7:30
Compression from ankle through knee	30 s	1:00	7:00
Effleurage from ankle through hip (4—5 full passes)	1 min	2:00	6:00
Petrissage and muscle stripping of upper leg	1 min	3:00	5:00
Petrissage and muscle stripping of lower leg	1 min	4:00	4:00
Petrissage and muscle stripping of anterior and posterior lower leg	1 min	5:00	3:00
Spread ball of foot with thumbs & thumb circles along full plantar surface	30 s	5:30	2:30
Friction and effleurage of posterior lower leg	1.5 min	7:00	1:00
Friction and effleurage of posterior upper leg	30 s	7:30	0:30
Effleurage and compression from ankle to hip (2—3 full passes)	30 s	8:00	0:00

tissue, which allows for the derivation of tissue blood oxygen saturation (StO_2) and blood volume (proportional to total hemoglobin concentration (THC)) (De Blasi et al., 1995; Fantini et al., 1999). The fast changes of dynamic optical property (rBF) are monitored using DCS (Figure 1d) with a long coherence length continuous wave laser at 785 nm and two single photon counting avalanche photodiode (APD) detectors. The light intensity fluctuations from a single speckle area of tissue surface are detected by the APDs connected with two single-mode fibers. A multi-channel autocorrelator takes the APD outputs and computes the light intensity temporal autocorrelation functions which are used to calculate the electric field temporal autocorrelation functions. The rBF is obtained from the change in autocorrelation function decay time, as measured by the autocorrelator and a computer interface. The two optical techniques are co-registered using multiple sources—detectors pairs (Figure 1b): 4 source-detector separations for NIRS (2, 2.5, 3, and 3.5 cm) and 2 separations for DCS (2.5 and 3 cm). Multiple separation measurements provide information about tissue heterogeneous responses at different regions and depths (Yu et al., 2005a). The complete set of source-detector measurements provides both averaged and local values of the tissue blood hemodynamics.

Proposed study purpose, study design, and sample data

The proposed pilot study will seek to quantify hemodynamic changes in deep muscle tissue after MT. Specifically, it will assess the acute response of blood flow and oxygenation to lower limb MT in both gastrocnemius muscles (left side treatment, right side control) of healthy young adults (18—35) using the hybrid NIRS/DCS instrument before and 20 min post massage. The specific MT procedure used in the proposed study was designed and provided by a Kentucky licensed massage therapist (N.M.) with eight years clinical and 5 years MT teaching experience. As described in Table 1, the procedure is 8 min long and is applied with participants in a prone position utilizing a bolster under their ankles and a pillow under their upper chest and head. In an effort to reflect MT as practiced, 8 min was selected for the duration of the MT procedure as this allotment reflects the approximate amount of time one leg would be massaged in a typical, 1 h, full-body MT session based on the clinical experience of the MT procedure's designer. A timed power point presentation will be used for each treatment in order to provide uniform consistency between sessions and participants in regard to contact time, body areas addressed, and technique order. The MT procedure consists of common massage *techniques* (Table 2) rather than massage *types* (i.e. Swedish, Sports, Trigger Point Therapy) to avoid confusion for future replication.

After consenting to participate in the study, participants lay in a comfortable prone position with bolster and pillow appropriately placed for the MT procedure. Participants were instructed to indicate if the MT procedure becomes uncomfortable at any time and to inform the therapist if the pressure becomes too deep. Through palpation, the belly of the medial gastrocnemius muscle is identified and optical probes secured on both legs using medical tape (Figure 3). Because the optical detectors (PMT and APD)

Table 2 Massage techniques and descriptions utilized in the MT procedure.

Massage therapy technique	Description
Effleurage	Long, gliding strokes
Petrissage	Kneading or lifting and grasping of the tissue with alternating hands
Compression	Sustained direct pressure with full or heel of the hand, often applied in a press and lift method
Muscle stripping	Continual gliding pressure with reinforced fingertips, thumbs, or knuckles applied to one muscle at a time starting at the muscle insertion and ending at the muscle origin
Friction	Small, deep movements applied with fingers that do not glide across the skin, rather rapidly move the skin perpendicular or at an angle to the muscle fiber direction

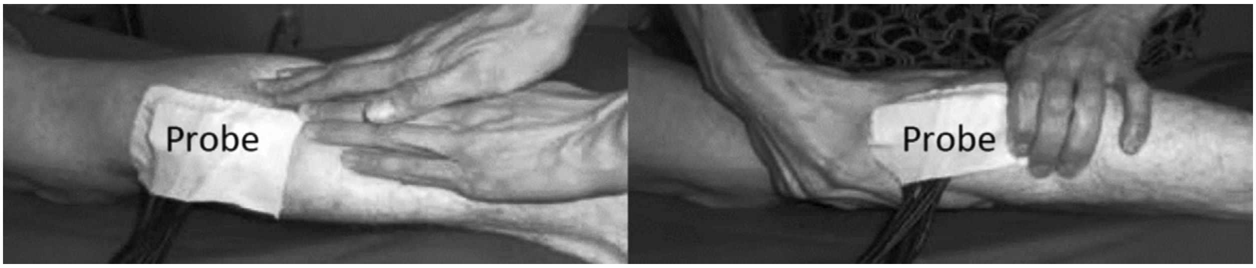

Figure 3 MT is applied to the entire treatment leg. While care is used around the optical probe (see Figure 1b) taped on the surface of medial gastrocnemius muscle, effleurage and petrissage strokes are easily administered to the tissue surrounding the secured optical probe.

used in the hybrid instrument are extremely sensitive to light, room lights are turned off once signal intensity is confirmed to avoid light influence on optical measurements. Talking is kept to a minimum in order to allow study participants to relax and for the environment to reflect the peaceful nature typical in MT practice. After 5 min of baseline measurements, the study therapist begins the MT procedure with firm pressure that increases in depth throughout the 8 min duration of the treatment (Figure 3). Efforts throughout the procedure keep all massage strokes fluid with smooth transitions between technique and location shifts. After massage completion, the therapist informs the participant to lie quietly in the same position for 20 min. Tissue blood hemodynamics were measured for 20 min post MT procedure. After the 20 min of optical measurement, the room lights were turned back on and the optical probes removed.

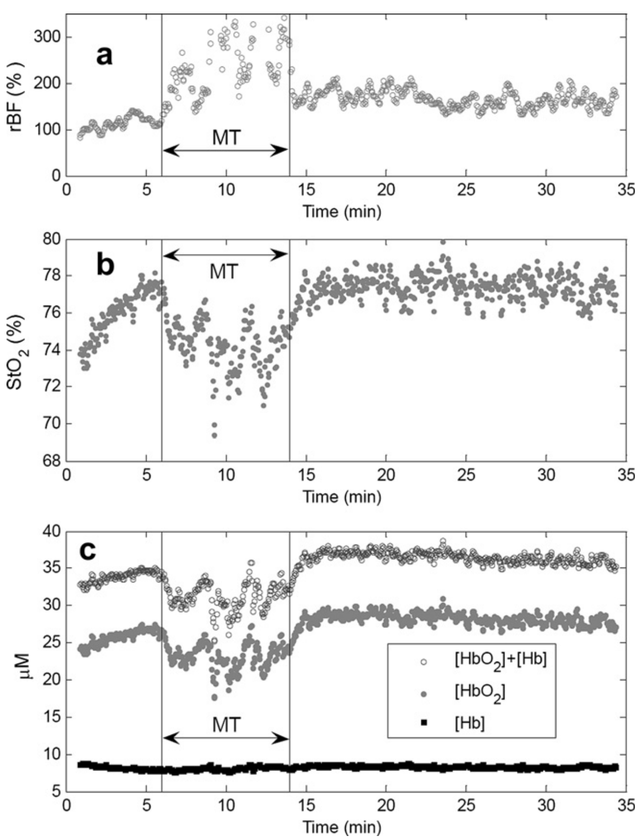

Figure 4 Data from a 28-year-old female demonstrates the muscle hemodynamic changes after MT collected by the hybrid instrument combining NIRS and DCS. (a) An increase from 100% to 142.5% in rBF was found following MT. (b) The tissue blood oxygen saturation (StO_2) increases from 75.9% to 77.3% following MT. (c) While the deoxy-hemoglobin concentration ([Hb]) does not change, the increase in oxy-hemoglobin concentration ($[HbO_2]$) primarily contributes to the total increase in blood volume ($[HbO_2] + [Hb]$) following MT.

Figure 4 shows graphical representations of sample study data collected with the hybrid NIRS/DCS instrument for a female pilot participant. The Medical Internal Review Board (IRB) at the University of Kentucky approved all preliminary and proposed study activities (approval #09-0636) and consent was obtained from the female pilot participant. DCS data obtained from the 2.5 cm source-detector (S-D) separation is used to extract muscle flow information. Although the 3.0 cm separation of S-D pair can probe deeper as light penetration depth is proportional to the S-D separation (Yu et al., 2005a), the 2.5 cm separation of S-D pair generates DCS data with higher signal-to-noise and has been used effectively to detect blood flow in muscle tissue (Shang et al., 2010; Yu et al., 2005a). NIRS (Imagent) data obtained from all source-detector separations are utilized to extract absolute tissue oxygenation information using a spatially resolved spectroscopy method (De Blasi et al., 1995; Fantini et al., 1999). The vertical lines at approximately 6 and 14 min in Figure 4 indicate the beginning and end of the MT procedure. While continuous measurement of hemodynamic properties occurs during the 8 min MT procedure (time period between the 6 and 14 min marks), the proposed study will use only pre and post measurements in analysis, as the muscle fiber motion artifact during MT may contaminate blood flow measurements (Shang et al., 2010). Figure 4a depicts rBF output from the treatment leg as gathered by the DCS aspect of the hybrid instrument. This sample data assigns the pre-MT baseline rBF (data to the left of the first vertical line) as 100%. The ~40% post-MT increase in rBF (data to the right of the second vertical line) suggests that the treatment had an acute effect in muscle blood flow. Figure 4b depicts blood oxygen saturation and Figure 4c shows blood volume (THC) and oxy- and deoxy-hemoglobin concentrations in the assessed muscle tissue. This pilot participant experienced small increases in muscle tissue oxygenation and blood volume following the MT procedure. These results are expected because the MT procedure involved such techniques as compression, effleurage, and petrissage which theoretically enhance tissue blood flow and oxygenation through manual pump-like mechanics. Nevertheless, it should be noted that all data presented here is for demonstration purposes only and does not reflect statistical analysis.

Discussion and conclusions

Utilization of the hybrid instrument (Figure 1) has the potential to collect muscle hemodynamic data while avoiding some of the drawbacks existing in other assessment methods discussed earlier. Specifically, the hybrid NIRS/DCS instrument is portable, unobtrusive, and quiet while placing less physiological stress on participants as it only requires an optical probe (Figure 1b) over the measurement area (Figure 3) rather than the ingestion or injection of a radiotracer as is required with PET and SPECT technology. Furthermore, measurements are obtained in real time using the hybrid NIRS/DCS instrument rather than requiring adjustments in positioning and additional time for imaging. Once an optical probe is secured over a muscle, MT may be applied to the surrounding area (Figure 3) ensuring that pre and post tissue measurements are of the same location. While expense often inhibits MT researchers from utilizing sophisticated tools such as PET or SPECT, the hybrid NIRS/DCS instrument may be more accessible due to its primary cost occurring at initial procurement of the instrument. Additionally, utilization of the hybrid NIRS/DCS instrument may allow researchers to measure MT effects on muscle hemodynamics in an environment that more accurately assimilates that found in MT clinical practice.

Previous MT studies investigating blood flow have actually used measures that do not directly assess the rBF. Rather, such studies make assessments of arterial width and blood velocity to extrapolate macro- hemodynamic properties or examine proxy assessments that are related to rBF such as oxygenation saturation levels or skin temperature. While meaningful data are gathered in studies which use these assessments, independently and directly measuring muscle rBF and oxygenation in MT studies is desirable to more fully understand the extent to which MT affects physiologic processes. NIRS/DCS technology provides direct and independent measurements of tissue blood flow and oxygenation (Figure 4), allowing MT researchers to explore specific MT protocols and how MT influences and benefits the tissue. Specifically, an increase in oxygenation may be only one beneficial aspect of an increase in rBF and is not the only interest for the massage field. For example, an increase in rBF would also enhance the delivery of other important nutrients to body tissue and the evacuation of cellular wastes. Proxy or estimation measures of blood flow or oxygenation measures are insufficient to address such hypotheses. Overall, the hybrid NIRS/DCS instrument addresses many of the limitations previously discussed regarding measurement options assessing MT effects on hemodynamic properties in humans.

The current proposed pilot study expects to clarify the debate on whether or not MT influences muscle hemodynamics by utilizing the hybrid instrument to directly measure both rBF and blood oxygenation in deep skeletal muscle before and after a specific MT procedure. It is expected that results from the proposed pilot study will serve as a foundation for future MT research employing the NIRS/DCS hybrid instrument to investigate MT effects on deep muscle hemodynamics in older and younger adults. Such investigations could also be conducted for clinical disorders, including diabetes, fibromyalgia, arthritis, and peripheral vascular disease, and may lead to the development of non-pharmacological means (e.g., MT) for efficiently promoting microvascular circulation in deep tissues.

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