Universidad Pública de Navarra,
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Compartimentalización Neuromuscular de los Músculos Vastus Medialis y Abductor Digiti Minimi en Personas Jóvenes

Neuromuscular Compartmentalization of the Vastus Medialis and Abductor Digiti Minimi Muscles in Young People.

TESIS DOCTORAL

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Abreviaturas

UMs : Unidades motoras

EMG: Electromiografía

EMGAD: Electromiografía de superficie de alta densidad

SNC: Sistema nervioso central

LIBFE: Laboratorio integrativo de Biomecánica y fisiología del Esfuerzo.

CVM: Contracción voluntaria máxima

PAUM: Potencial de acción de unidades motoras

RMC: Raíz media cuadrática

VC: Velocidad de conducción

ZI: Zona de inervación

VM: vastus medialis

VMO: Vastus medialis obliquus

VML: Vastus medialis longus

IMC: Índice de masa corporal.

ADM: Abductor digiti minimi

FC: Functional compartments

BW: Body weight

CONC: Concentric

ISO: Isometric

ECC: Excentric.

GRF: ground reaction force

NMC: Neuromuscular compartmentalisation

MVC: Maximal voluntary contractions

RMS: Root mean square

Z1: dorsal zone

Z2: dorsal-palmar zone

Z3: palmar zone

Declaración

Yo, Rodrigo Antonio Guzmán Venegas, declaro que la investigación presentada en esta tesis se basa en 2 artículos (capitulo II y III), de los cuales el primero se encuentra publicado en una revista internacional y el segundo está aceptado. Declaro que los artículos presentados en este documento de tesis corresponden a versiones fieles del publicado y aceptado.

También declaro que todos los procedimientos llevados a cabo las personas que participaron como voluntarios contaron con la aprobación del Comité Ético Científico de la Universidad de los Andes de Chile, comité acreditado por la SEREMI de Salud Metropolitana bajo la resolución exenta Nº010569. Las actas de aprobación para ambas investigaciones corresponden a SCEC201603 (07-03-2016) y SCEC201824 (2018-15-05-2018).

Por último, declaro que mi participación en las investigaciones presentadas en esta tesis incluyeron, la elaboración en el diseño del estudio, el análisis de datos e interpretación de resultados, y la redacción de los trabajos incluidos en la presente tesis

Resumen

Existe evidencia que evidencia que el reclutamiento de unidades motoras dentro de un mismo músculo presenta cierta heterogeneidad. Esta heterogeneidad en la activación de las unidades motoras ha llevado a la hipótesis de que ciertos músculos podrían organizarse neuromuscularmente como compartimentos funcionales, más allá de la existencia demostrable de estos a nivel morfológico. Esto implicaría que las unidades motoras agrupada en determinadas regiones musculares tendrían diferentes niveles de activación que unidades motoras ubicadas en otras zonas del mismo músculo. Varios estudios han evidenciado la existencia del reclutamiento diferencial de los músculos del tronco y las extremidades, demostrando la existencia de una compartimentación funcional. Esta tesis buscó demostrar la existencia de una compartimentación funcional en los músculos *Vasto Medial* y *Abductor Digiti Minimi* en personas jóvenes.

Estudio I

Estudios anatómicos describen que el vasto medial (VM) está subdividido en dos componentes morfológicamente identificables, el vastus medialis obliquus (VMO) y el vastus madialis longus (VML). Sin embargo, existe discrepancia acerca de la diferenciación funcional de estos componentes. El objetivo de este estudio fue comparar mediante electromiografía de superficie de alta densidad los niveles de activación del VMO y VML.

Doce mujeres jóvenes sanas (age: 21.4±2.0 years; weight: 58.1±7.5kg; height: 1.6±0.1m), realizaron un ejercicio de cadena cinética abierta de rodilla, durante el cual se registró la actividad EMG del VMO y VML con matrices bidimensionales de 32 electrodos de superficie. Los ejercicios se realizaron con tres niveles de resistencias (5, 10 y 15% del peso corporal [BW]), considerando tres fases: concéntrica, isométrica y excéntrica.

En la fase isométrica el VMO tuvo mayor activación que el VML en los tres niveles de resistencia ($p<0.05$). En la fase excéntrica, el VMO también registró mayor activación que el VML en las resistencias de 10 y 15%BW. Mientras que, en la fase concéntrica, el VMO mostró mayor nivel de actividad que el VML, sólo al 15%BW.

Los resultados indicaron diferencias significativas en los niveles de activación entre ambos componentes del VM. Esto resulta importante para el desarrollo de ejercicios que busquen una activación mayor o más selectiva del VMO.

En la muestra evaluada, los registros de EMG describen una mayor activación del VMO en comparación al VML, la cual es más importante en las fases isométricas y excéntricas de la flexión/extensión de rodilla en cadena cinética abierta. Estos hallazgos sugieren una compartimentalización funcional del VM.

Estudio II

Existe evidencia que demuestra la presencia de una compartimentalización funcional (CF) en algunos músculos esqueléticos. Aquello se traduce en que las unidades motoras (UM) agrupadas en ciertas zonas del músculo, presentan diferentes niveles de activación a las ubicadas en otras regiones. Esto solo ha sido descrito en músculos grandes, cuya morfología justifica la existencia de una CF. Sin embargo, no existen antecedentes de aquello en músculos pequeños, tales como el *abductor digiti minimi* (ADM). El objetivo de este estudio fue comparar la activación de las UM en distintas zonas del ADM, con la finalidad sostener la hipótesis de la existencia de una CF en el ADM.

Mediante un estudio observacional analítico transversal se evaluó la actividad de las UM del ADM en 12 voluntarios (edad 21±1.6 años; peso 75.3±8 kg; altura 176.2 ± 7.3 cm; promedio ± desviación estándar). La actividad de las UM, se evaluó mediante electromiografía de superficie alta densidad usando una matriz de 64 electrodos dispuestos bidimensionalmente. Esta permitió registrar la actividad de las UM en tres zonas del ADM (Z1: zona dorsal; Z2: zona dorso-palmar y Z3: zona palmar). Los registros electromiográficos fueron obtenidos durante contracciones isométricas voluntarias del ADM al 20, 40, 60 y 80% de la contracción voluntaria máxima (CVM). La comparación de los niveles de activación de las UM entre las tres zonas fue realizada mediante un análisis de modelos mixtos de covarianza. Los resultados indicaron que existió diferencia significativa entre la zona dorsal y palmar al 40% de la CVM ($p=0.03$), y entre la zona dorsal y dorso-palmar al 80% de la CVM ($p=0.03$). Los resultados obtenidos en la muestra evaluada sostienen la hipótesis de la existencia de una CF en el

ADM. Sin embargo, son necesarias más investigaciones para establecer con mayor certeza la presencia de esta compartimentalización en el ADM.

Abstract

There is evidence that supports that the recruitment of motor units within the same muscle presents a certain heterogeneity. This heterogeneity in activation has led to the hypothesis that certain muscles could be organised neuromuscularly as functional compartments, beyond the existence that is demonstrable at a morphological level. This would imply that the motor unit grouped in certain muscle regions would show different activation levels that differ from the motor units located in other zones of the same muscle. Several studies have evidenced the existence of differential recruitment of the muscles on the trunk and limbs, demonstrated the existence of functional compartmentalization in that. This thesis sought to demonstrate the existence of a functional compartmentalization in Vastus Medialis and Abductor Digiti Minimi muscles in young people.

Study I

Anatomical studies describe the vastus medialis (VM) as being subdivided into two morphologically distinct components, the vastus medialis obliquus (VMO) and the vastus medialis longus (VML). However, there are discrepancies regarding the functional differentiation of these components. The aim of this study was to compare the levels of activation of the VMO and the VML by high density surface electromyography.

Twelve healthy young women (age: 21.4 ± 2.0 years; weight: 58.1 ± 7.5 kg; height: 1.6 ± 0.1 m), performed an open kinetic chain knee exercise during which the EMG activity of the VMO and the VML was recorded with two-dimensional matrices of 32 surface electrodes. The exercises were performed with three levels of resistance (5, 10 and 15 % of the body weight (BW)), considering three phases: concentric, isometric and excentric.

In the isometric phase the VMO had greater activation than the VML with the three levels of resistance ($p<0.05$). In the excentric phase, the VMO also showed greater activation than the VML with the 10 and 15 % BW resistance levels, while in the concentric phase, the VMO showed greater activity than the VML-with only the 15 % BW resistance.

The results indicated significant differences in the activation level of the two components of the VM. This bears importance in the development of exercises intended to achieve a greater or more selective activation of the VMO.

In the sample subjected to evaluation, the EMG recordings describe a greater activation of the VMO in comparison to the VML, which is more important in the isometric and excentric phases of the flexion/extension of the knee in an open kinetic chain. These findings suggest a functional compartmentalization of the VM.

Study II

There is evidence demonstrating the presence of functional compartmentalization (FC) in some skeletal muscles. This means that the motor units (MU), grouped in certain areas of the muscle, show different levels of activation in comparison to those located in other zones. This has only been described in large muscles whose morphology proves the existence of a FC. However, there is no background information about small muscles, such as the *abductor digiti minimi* (ADM). The objective of this study was to compare the activation of the MU in different zones of the ADM to support the hypothesis of the existence of a FC in the ADM.

By using a cross-sectional, analytical, observational study, the activity of the MUs in the ADM was assessed in 12 volunteers (age 21 ± 1.6 years old; weight 75.3 ± 8 kg; height 176.2 ± 7.3 cm; average ± standard deviation).

The activity of MUs was evaluated using high-density surface electromyography (HD-sEMG) with an array of 64 electrodes arranged two-dimensionally. This allowed us to record the activity of the MUs in three zones of the ADM (Z1: dorsal zone; Z2: dorsal-palmar zone and Z3: palmar zone). Electromyographic recordings were obtained during voluntary isometric contractions of the ADM at 20, 40, 60 and 80% of the maximum voluntary contraction (MVC). The comparison of the activation levels of MUs between the three zones was carried out using a mixed model analysis of covariance. The results showed a significant difference between the dorsal and palmar zones at 40% of the MVC ($p= 0.03$), and between the dorsal and dorsal-palmar zone at 80% of the MVC ($p= 0.03$). The results obtained in the evaluated sample support the hypothesis of the existence of

FC in the ADM. However, further research is needed to determine with greater certainty the presence of this compartmentalization in the ADM.

Listado de Publicaciones.

Esta Tesis Doctoral se presenta como un compendio de dos artículos:

1.- Rodrigo Guzmán-Venegas; Oscar Valencia; Eduardo L. Cadore & Mikel Izquierdo. Neuromuscular compartmentalization of the vastus medialis: comparison of the activity of the vastus medialis obliquus and the vastus medialis longus by high density electromyography. **Int. J. Morphol., 39(1):205-210, 2021.**

2.- . Rodrigo Guzmán-Venegas; Mikel izquierdo; Eduardo Cadore & Juan Carlos López. Comparison of the electromyographic activity of different zones of the abductor digiti minimi manus muscle in search of a functional compartmentalization. **Aceptado . Int. J. Morphol.,**

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Dedico esta tesis a mi amada esposa Carolina que con su amor y paciencia infinita, me ha apoyado y dado animo...

A mis hijos Martina, Catalina, José Ignacio y Emilia ……por su inmenso amor y alegría, y por todas las horas que les adeudo…

A mis padres y hermanos…

A la Santísima Virgen por su inmenso amor de madre…

Capítulo I

Descripción general y conceptos básicos

INTRODUCCIÓN

El músculo esquelético es un tejido altamente especializado. Este está constituido principalmente por fibras musculares, las cuales son inervadas por las alfa motoneuronas, esta relación morfo-funcional da origen a las unidades motoras (UMs). La actividad de estas determina el patrón de reclutamiento muscular, que define cuando y cuanto se activa un músculo durante la realización de una tarea motora. Mediante algunas técnicas de instrumentación, es posible realizar la descripción de estos patrones. Clásicamente se ha utilizado la técnica de electromiografía (EMG). En ella, la actividad de un músculo es representada por los registros obtenidos por electrodos ubicados en puntos anatómicos determinados. En esta técnica se asume que la actividad EMG registrada en dicho sitio es extrapolable al resto del músculo, lo cual puede significar una desventaja, por asumir que todas las UMs se activan de manera uniforme. En este sentido, la compleja arquitectura muscular, hace presumir que existiría una diferenciación en el nivel de activación de las UMs según su ubicación dentro del músculo. Existe evidencia que demuestra la presencia de divisiones funcionales al interior de los músculos. De esta forma las unidades motoras podrían ser reclutadas en forma diferencial, con relación al nivel de fuerza requerida, o bien, a las características de la tarea motora realizada. La técnica que ha permitido el estudio de esta compartimentalización funcional es la EMG de superficie de alta densidad (EMGAD), técnica que consiste en el uso de matrices de varios electrodos (4 hasta 400) dispuestos en línea o en matrices bidimencionales. Estas últimas permiten registrar simultáneamente la actividad de las UMs ubicadas en diferentes regiones de un mismo músculo.

En esta tesis doctoral, se ha investigado *in vivo* mediante la técnica de EMGAD, la compartimentalización funcional de los músculos *Vastus Medialis* y *Abductor Digiti Minimi* en personas jóvenes. Con la finalidad de responder la siguiente pregunta de investigación:

En los músculos *Vastus Medialis* y *Abductor Digiti Minimi* de jóvenes sanos ¿Presentan una compartimentalización funcional?

Por ello el objetivo asociado a la pregunta anteriormente plantada fue describir la distribución topográfica de la actividad de las unidades motoras de los músculos *Vastus Medialis* y *Abductor Digiti Minimi* utilizando EMGAD, para evaluar la siguiente hipótesis: "Los músculos *Vastus Medialis* y *Abductor Digiti Minimi* tienen una compartimentación funcional in vivo, medida con EMGAD.”.

1.- Compartimentalización funcional.

El músculo esquelético está constituido por fibras musculares y tejido conectivo que se organiza en diferentes niveles dando origen a la estructura de este órgano (12). Sin embargo, la unidad funcional del músculo esquelético son las unidades motoras (UMs), las cuales están constituidas por un número determinado fibras musculares (decenas hasta miles, dependiendo del músculo) que son inervadas por una misma alfa-motoneurona. La activación de dichas UMs, por el Sistema Nervioso Central produce la contracción muscular, con la que se da origen a la fuerza muscular, responsable de la estabilidad articular y de los movimientos de los segmentos corporales. Existe evidencia que sostiene la hipótesis que el reclutamiento de las UMs al interior de un mismo músculo presenta una cierta heterogeneidad. Basmajian (2) es uno de los primeros autores que describe en humanos, el reclutamiento heterogéneo de unidades motoras de un mismo músculo, interpretándolo como parte de la funcionalidad de este. Más tarde Campbell et al. (5) describen la heterogeneidad en la activación del tríceps sural durante la bipedestación combinada con diferentes posiciones de los pies y los tobillos. Sus resultados los llevan a proponer una organización funcional constituida por cuatro compartimientos funcionales. Luego, Soderberg and Dostal (26), describen durante la marcha y en el ascenso y descenso de escaleras, la existencia, en el glúteo medio, de tres compartimentos, los cuales muestran tener diferentes niveles de activación. Paré et al. (23) investigaron la existencia de una diferenciación funcional entre la activación de las fibras anteromediales y posterolaterales del tensor de la fascia lata. Ellos describieron que durante el trote y la carrera, las fibras anteromediales fueron más activas cerca del despegue del pie desde el suelo, mientras que las posterolaterales incrementaron su actividad durante el contacto inicial del pie con el suelo. Paton and Brown (24) demostraron la activación diferencial de seis regiones distintas del pectoral mayor, durante la ejecución de diferentes movimientos de hombro. Ellos proponen el término de diferenciación funcional de las UMs, refiriéndose a la capacidad del SNC para controlar de manera independiente el nivel de activación de las unidades motoras ubicadas en un segmento particular en el interior de un mismo músculo, haciendo alusión a la existencia de una compartimentalización funcional.

Los resultados de las diversas investigaciones presentados hasta aquí, indican la presencia de reclutamiento heterogéneo de algunas porciones específicas del músculo en relación a la función o el nivel de fuerza desarrollado. Estos hallazgos podrían indicar que la distribución de los tipos de fibras musculares en el interior del músculo, no sería simplemente al azar, sino que tendría una organización predeterminada, la cual configuraría el reclutamiento diferenciado y con ello la compartimentalización funcional del músculo, tal como se ha demostrado en modelos animales (6). Reciente el mismo autor de esta tesis ha demostrado la existencia de una compartimentalización funcional del musculo masetero superficial(13).

2.- Unidades Motoras Musculoesqueléticas.

La unidad motora es la unidad funcional básica del sistema neuromuscular. Esta consiste en una neurona motora del asta anterior de la medula espinal o tronco cerebral, su axón y las fibras musculares que esta inerva (16, 25). A través la regulación de la actividad de las unidades motoras el sistema nervioso central controla la producción de fuerza muscular y con ello los movimientos de los segmentos corporales. El número de unidades motoras que contiene cada músculo, se relaciona con su tamaño y función, así músculos pequeños pueden tener diez unidades motoras, mientras que músculos grandes pueden presentar cerca de 1500, algunos ejemplos de ello son presentados en la tabla 1.1.

Tabla 1.1. Descripción del número de axones, fibras musculares y zonas de inervación de tres músculos esqueléticos.

Músculo	Axones Motores	Fibras musculares	Zonas de Innervación
Masetero[a]	1452	929.000	640
Temporal[a]	1331	1.247.000	936
Biceps Brachii[b]	774	580.000	750

[a] Adaptado de Carlsoo S. Acta Morphol Neerl Scand. 1958;2(1):13-9.(18)

[b] Adaptado de Christensen E. Am J Phys Med. 1959;38(2):65-78. (7)

2.1.- Clasificación de UMs.

Desde una perspectiva didáctica, las UMs pueden ser clasificadas según su tamaño, velocidad de contracción y función.

En relación al tamaño las UMs, estas pueden ser clasificadas en pequeñas y grandes. Las primeras inervan un pequeño número de fibras musculares, mientras que las segundas lo hacen a grandes grupos de fibras. La implicancia funcional de aquello, radica en que una regulación fina de la fuerza es desarrollada por músculos que contienen predominantemente UMs pequeñas, como por ejemplo los músculos extra oculares, los cuales debe generar movimientos extremadamente precisos y finos. Otra característica importante es que las UMs pequeñas están constituidas por motoneuronas de somas pequeños y axones de bajo diámetros, que descargan a frecuencias entre 10-20Hz, mientras que las UMs grandes, están conformadas por motoneuronas de somas de mayor tamaño y axones más gruesos, con mayores frecuencias de descargas (30-60Hz). El tamaño de los somas, también tendría una implicancia funcional, dado que los umbrales de excitación de las motoneuronas, y por ello de las UMs, tendría relación con dicho tamaño. De esta forma, las UMs pequeñas tendrían menores umbrales de excitación que las grandes. Este fenómeno fue explicado por Henneman (14, 15), quien lo describió como el *Principio del Tamaño.* Este establece que existe un orden en reclutamiento de las UMs en relación al tamaño de estas y la magnitud de la fuerza producida. Así, para la producción de fuerza muscular de baja intensidad, son reclutadas las UMs pequeñas, y en la medida que la magnitud de fuerza se incrementa, se reclutan UMs grandes.

Las UMs también pueden ser clasificadas según su velocidad de contracción. De este modo pueden ser divididas en UMs lentas o rápidas. Las UM lentas están constituidas por fibras lentas o tipo I, que son de relativo pequeño diámetro. Las UMs rápidas en cambio, están constituidas principalmente por fibras tipo II, que presentan diámetros comparativamente mayores a las de tipo I.

En relación a la función de las UMs, estas pueden ser clasificadas en tónicas o fásicas. Las primeras son principalmente UMs pequeñas y lentas, que gracias a su alta resistencia a la fatigabilidad cumplen funciones tales como la mantención de la postura corporal y el tono muscular. Estas participan en la graduación fina de la fuerza y el control de movimientos precisos. Por otro lado, las UMs fásicas, son grandes y rápidas, las cuales participan en la producción de fuerzas de mayor magnitud y movimientos más gruesos.

También es importante mencionar que existen UMs de características intermedias en cuanto al tamaño y velocidad de contracción, en las cuales predominan las fibras tipo IIA.

2.2. Reclutamiento de unidades motoras y la generación de fuerza muscular.

El reclutamiento de las UMs puede ser llevado a cabo de manera independiente entre las UMs de un mismo músculo, en otras palabras, a un instante determinado una UMs puede estar activada, mientras que su vecina esta inactiva, o sea, las UMs pueden ser reclutadas de manera alternada o asincrónica. La fuerza que puede generar un músculo depende de la actividad de sus unidades motoras, específicamente de la cantidad de unidades motoras activas y de la frecuencia de descarga de estas (1). La figura 1.1 muestra un ejemplo del reclutamiento de unidades motoras y de la frecuencia de descarga de estas durante una contracción muscular isométrica incremental.

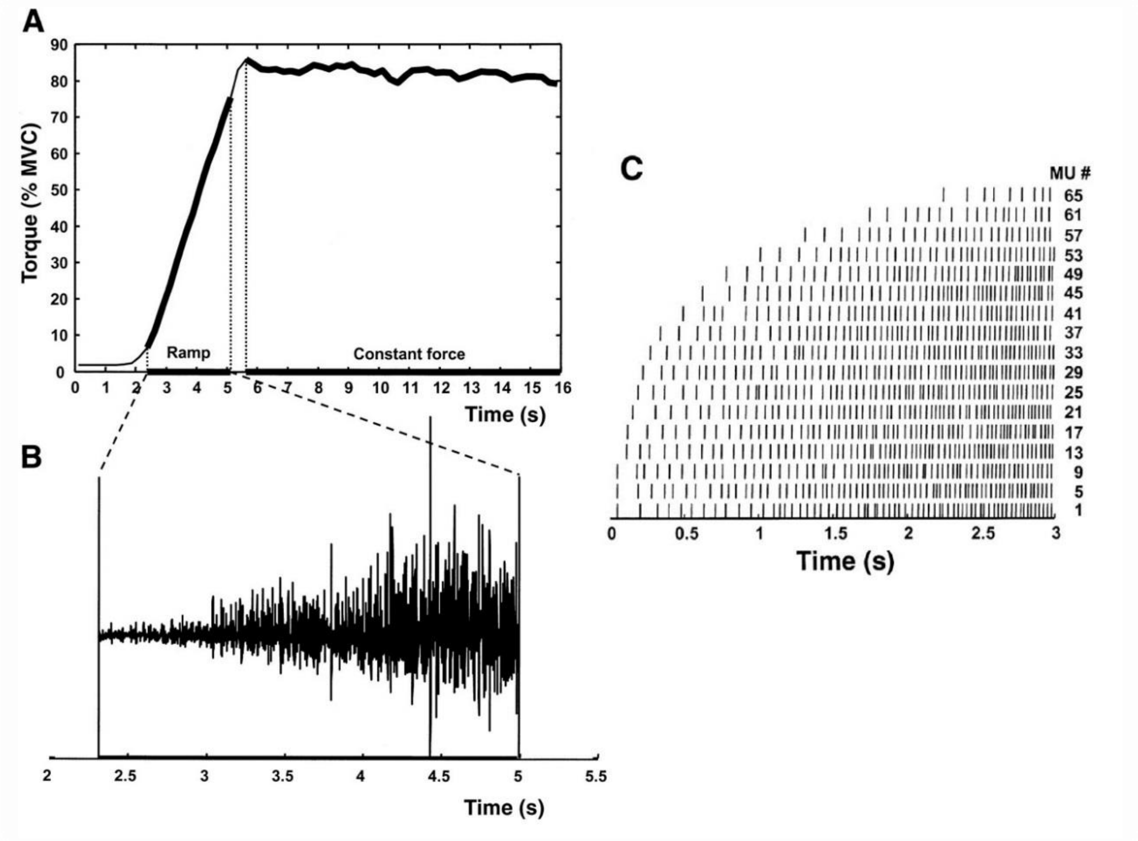


Figura 1.1. Reclutamiento de unidades motoras y su frecuencia de descarga durante la generación progresiva de fuerza isométrica. A.- Registro de torque isométrico de rodilla expresado como un porcentaje de la contracción voluntaria máxima (CVM). B.- Registro electromiografico de superficie del vasto lateral de cuádriceps. C.- comportamiento de diecisiete unidades motoras obtenido mediante descomposición de

señales electromiografías de superficie. Cada unidad motora está asignada por un número entre 1-65, cada línea vertical designa una descarga de cada unidad motora. Nótese que frente al incremento de la magnitud de torque se observa un incremento de las unidades motoras activas y un aumento de la frecuencia de descarga de estas. Tomado de (11)

Existen varias teóricas acerca de la forma en que el sistema nervioso central (SNC) ejerce su control sobre las UM. Una de las que ha presentado mayor sustento experimental es la teoría de la Conducción Común (*common drive theory*) (10). Esta teoría establece que al interior de un musculo existirían grupos o clanes de UMs que responderían a un comando común, este comando ejercería control sobre dicho clan, y no sobre otros. Este mecanismo de cierta forma descargaría de trabajo al SNC, dado que este ejercería su control sobre dichos comandos, y no sobre cada UMs de manera individual. La evidencia experimenta de dicha teoría se basa en la presencia de grupos de unidades motoras que presentan una sincronización de sus frecuencia de descarga, fenómeno denominado "tela de cebolla" (*onion skin*)(8). La figura 1.2, muestra un ejemplo de la sincronización en la frecuencia de descarga de varias unidades motoras.

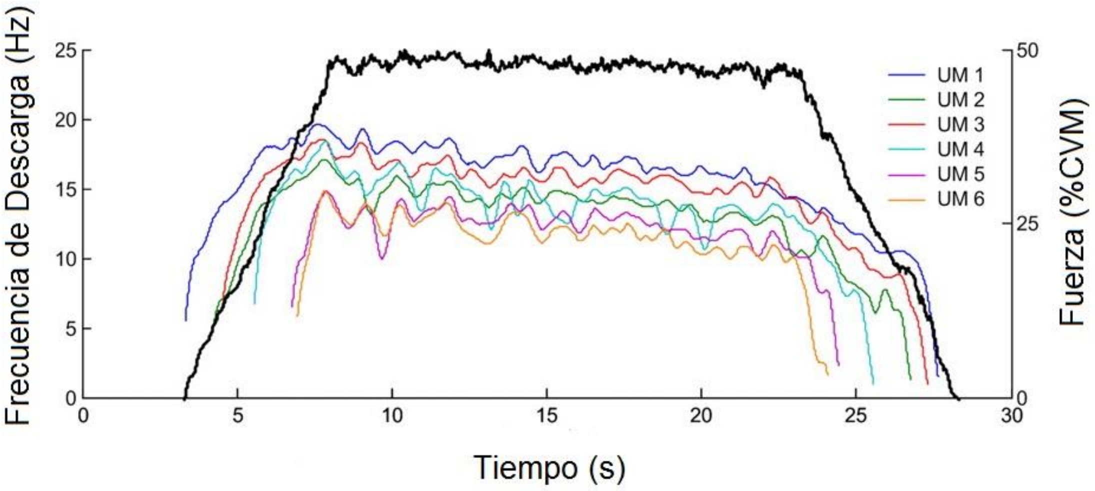


Figura 1.2. Sincronización de la frecuencia de descarga de Unidades Motoras. La figura muestra la frecuencia de descarga de seis UMs, durante la realización de una contracción isométrica al 50% de la contracción voluntaria máxima (CVM). Nótese como por un lado las UMs 5 y 6, y por otro, las 1 y 3, presentan una sincronización de sus frecuencias de descargas. Tomado de De Luca & Contessa (9).

3.- Electromiografía.

La electromiografía es una técnica de electrofisiológica que estudia el sistema neuromuscular, mediante la captura y análisis de la actividad eléctrica del músculo. Esta última tiene su origen en la activación de las unidades motoras y la concomitante generación de sus potencias de acción (PAUM). Mediante esta técnica es posible obtener una señal EMG, la cual corresponde, a la suma algebraica de todos los PAUM generados por todas las unidades motoras activas dentro de la zona determinada de registro (3). La figura 1.3 muestra una señal EMG típica. En la adquisición de dichos potenciales se pueden usar variados tipos de electrodos, los cuales pueden ser clasificados en dos grandes grupos: i.- intramusculares, y ii.- de superficie (figura 1.4). Los primeros, se caracterizan por atravesar la piel, para ser insertados dentro del tejido muscular, implicando un procedimiento invasivo. Esta técnica es utilizada para obtener registros con fines diagnósticos y para investigaciones que involucran músculos profundos. Por el contrario, los electrodos de superficie, no son invasivos, dado que se ubicar en la piel inmediatamente sobre los músculos estudiados. Esta técnica es aplicada a músculos superficiales, y es utilizada en investigación y evaluaciones clínicas de tipo funcional.

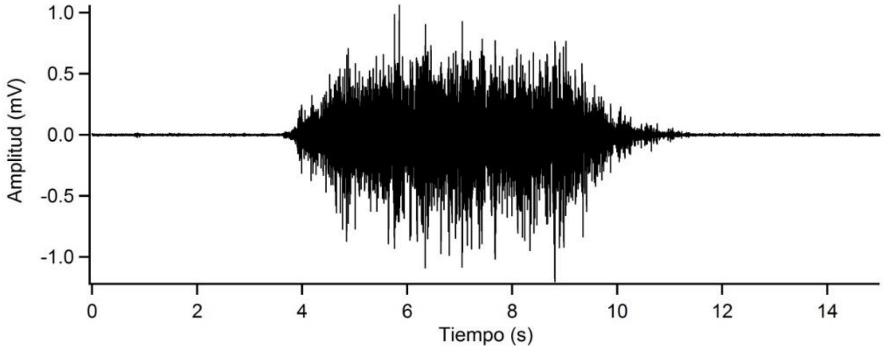
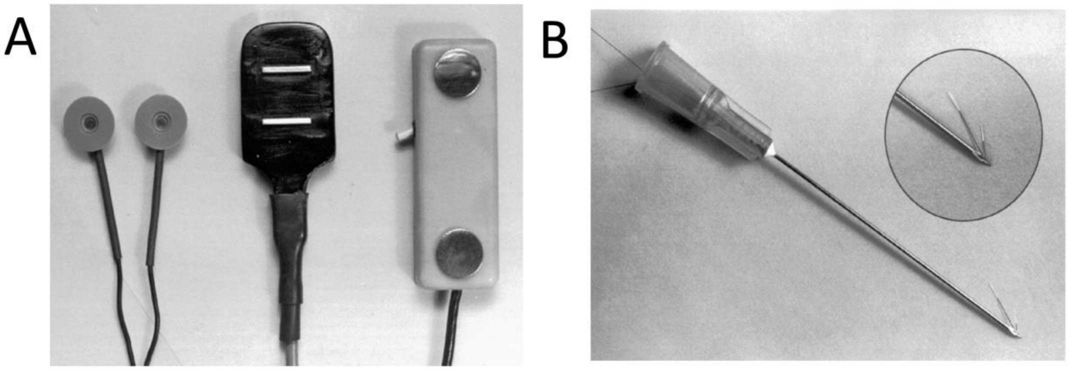


Figura 1.3. Señal electromiografía capturada en el músculo masetero superficial. En el procedimiento se emplearon electrodos de superficie, una amplificación de tipo diferencia simple con una ganancia de 2048Hz y una amplificación de 2000. Registro adquirido en el laboratorio Integrativo de Biomecánica y fisiología del Esfuerzo (LIBFE). Universidad de los Andes. Santiago. Chile.

Figura 1.4. Tipos de electrodos utilizados en electromiografía. A. electrodos de superficie, de izquierda a derecha. Electrodos discoideos pasivos; electrodo activo de barras paralelas; electrodo activo discoideo. B. electrodo intramuscular tipo alambre fino, la aguja hipodérmica es utilizada para insertar el electrodo, que es destacado en el círculo.



La señal EMG es de naturaleza estocástica, su amplitud presenta una *distribución* gaussiana, cuya magnitud fluctúa entre los 0 a 10 mV (pico-a pico), o bien, 0 a 1.5 mV en la escala de raíz media cuadrática (RMC). La banda de frecuencia de esta señal EMG de superficie esta entre 0 a 500 Hz, presentando una energía dominante en la banda de 50-150Hz, en la figura 1.5, se muestra un espectro de frecuencia típico de una señal EMG de superficie.

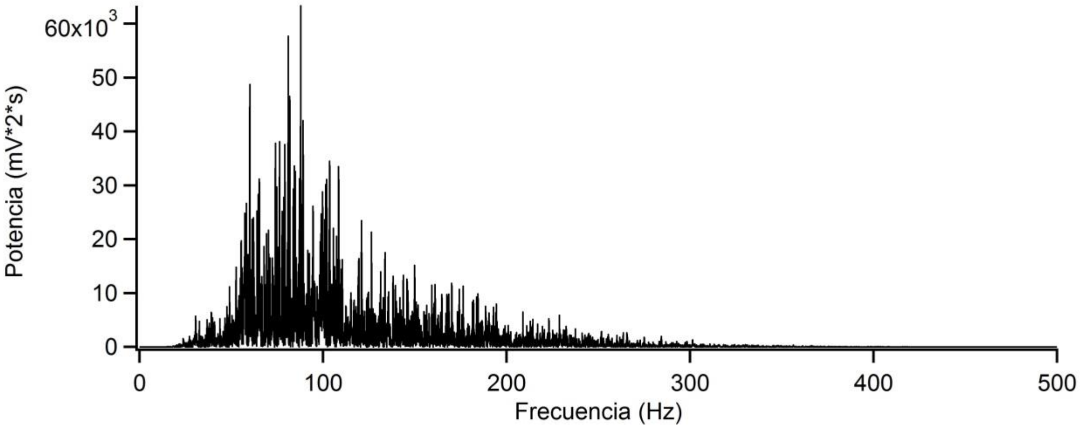


Figura 1.5. Espectro de frecuencia de una señal electromiografica de superficie capturada en el músculo masetero superficial. Nótese que la energía dominante se encuentra entre los 50-150Hz. Registro adquirido en el laboratorio Integrativo de Biomecánica y Fisiología del Esfuerzo (LIBFE). Universidad de los Andes. Santiago. Chile.

3.- Electromiografía de Alta densidad.

La electromiografía de superficie de alta densidad (EMGAD), es una técnica de EMG, la cual se diferencia de la EMG tradicional que utiliza uno o dos electrodos, emplea un número mayor de electros, dispuestos en una o dos dimensiones. El uso simultáneo de varios electrodos para registrar un solo músculo, se utilizó inicialmente para estimar la velocidad de conducción (VC) de los PAUM. Para ello, Bucthal et al (4), usó tres pares de electrodos intramusculares concéntricos insertados en línea, mediante los cuales estimó la VC y la ubicación de la zona de inervación del bíceps braquial. Más tarde Lynn (17), midió en el mismo músculo la VC, usando tres de superficie, dispuestos linealmente, documentando por primera vez la medición de dicho parámetro mediante un procedimiento no invasivo. Posteriormente, Nishizono et al. (22) también utilizaron esta disposición de electrodos para estimar la VC, sin embargo, incrementaron su número a ocho. Más tarde Masuda et al. (18), desarrollan un grupo quince electrodos de superficie dispuestos a manera de hilera, lo que le permitió describir la propagación de los PAUM a lo largo de las fibras musculares del bíceps braquial; lo que les permitió hacer una descripción de las ubicación de las ZI de ambas cabezas de este músculo, de manera no invasiva. Este mismo autor, más tarde, aplicó dicha técnica a varios músculos de las extremidades inferiores y superiores (19). Un año después, estos mismos autores (20) desarrollaron una disposición bidimensional de electrodos de superficie dispuestos en una cuadricula, dando así paso al desarrollo de las matrices bidimensionales de electrodos de superficie.

En la actualidad las tres principales aplicaciones de la EMGAD son (21):

1. El estudio del comportamiento de las unidades motoras mediante descomposición de las señales EMGAD.
2. La medición de la velocidad de conducción de los PAUM.
3. La descripción topográfica de la actividad EMG.

La figura 1.6 muestra un ejemplo de electrodos de superficie dispuestos en una y dos dimensiones.

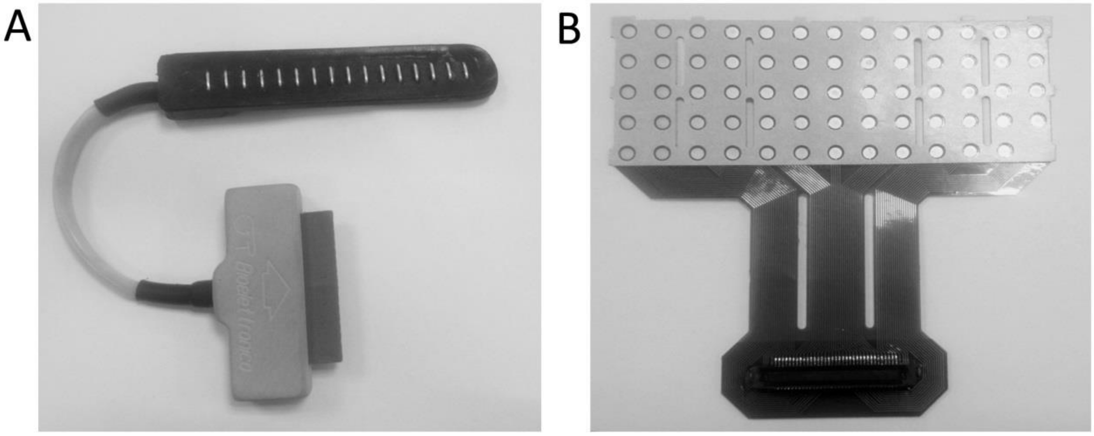


Figura 1.6. Ejemplos de electrodos de electromiografía de superficie de alta densidad. A.- Disposición unidimensional de dieciséis electrodos de superficie con una distancia interelectrodo de 5mm (modelo SA 16/5, Otbioelettronica, Torino, Italia). B.- Cuadricula o matriz bidimensional de sesenta y cuatro electrodos de superficie, con una distancia interelectrodo de 8mm (modelo ELSCH064NM2, Otbioelettronica, Torino, Italia).

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Capítulo II

Neuromuscular compartmentalization of the vastus medialis: comparison of the activity of the vastus medialis obliquus and the vastus medialis longus by high density electromyography

Introduction.

The vastus medialis (VM) is one of the components of the quadriceps muscle, whose main function is the extension of the knee and which, in particular, has been attributed an active role in the medial stability of the patella (25). Hence the clinical importance of its function in relation to the aetiology and treatment of patellofemoral dysfunction. This is one of the most prevalent knee pathologies in the young population, especially in women (19). The stabilizing role of the VM is mainly due to the orientation of its muscle fibres, the direction of which determines a medialising component of the patella (25). Anatomical studies show there is a structural division of the VM into two elements, the vastus medialis obliquus (VMO) and the vastus medialis longus (VML) (16, 20, 24). The fibres of these components are oriented at 47° and 15° respectively from the longitudinal axis of the femur (25). This morphologic characteristic leads to the presumption that each of these two components fulfils different functions, given the orientation of their lines of force (1, 8). In this context, the VML has been attributed primarily a knee extensor role, while the VMO is the only active medial stabilizer of the patella (22). Several studies have attempted to demonstrate the functional differences between these two components, nevertheless, their conclusions differ (Hubbard & Operstehy, 2002; Rainoldi et al., 2008; Spairani et al., 2012). A possible explanation for this lies in the techniques used to obtain the EMG recordings. On the one hand, needle EMG involves taking an intramuscular recording with a reduced capture volume, reason for which its recordings involve a small number of motor units (MU) and thus its conclusions are limited to the activation of those few MU (11, 12). This may be solved with bipolar surface EMG, a technique which involves a larger capture volume, incrementing in this way the number of MU it is capable of recording. However, in the case of large muscles, such as the VMO and the VML, the ratio between the capture volume and the muscle volume continues to imply that it leads to conclusions based on recording a reduced number of the total amount of MU. In contrast to the above, high density surface EMG (HD-sEMG) (2, 9, 11, 18) is a technique that employs a greater amount of electrodes arranged in one- or two-dimensional matrices which cover a large surface of the muscle being studied and thus a greater capture volume. Hence, the conclusions obtained with this technique imply a large number of MU and, consequently, also imply results which are possibly closer to reality (12). The aim of this research was to compare the level of activation of the VMO to that of the VML in young women during a knee flexion/extension exercise using HD-sEMG to test the hypothesis that the VMO presents a greater level of activation than the VML, with the purpose of providing evidence of the functional or neuromuscular compartmentalization of the VM.

Materials and methods

A sample of 12 physically active young women (age: 21.4 ± 2.0 years; weight: 58.1 ± 7.5 kg; height: 1.6 ± 0.1 m) was evaluated in a cross sectional analytic observational study (6). The following exclusion criteria were applied when recruiting volunteer participants: i) history of pain or pathology of the knee within the last 12 months, ii) medical history of central or peripheral neurological diseases, iii) injury or infection of the skin over the VM muscle, iv) substance abuse (alcohol and/or drugs) in the 48 hours prior to the evaluation, v) having performed strenuous physical activity in the 48 hours prior to the measurement. All volunteers provided written agreement signing an informed consent document. The procedures in this study were in accordance with the criteria of the Declaration of Helsinki and were approved by the local ethics committee (SCEC201603, 07-03-2016).

Exercise

The EMG activity of the VMO and the VML was recorded during an open kinetic chain flexion/extension exercise of the knee. The recordings were performed on the dominant knee of each volunteer determined on the basis of the lower limb selected most frequently to descend from a 30 cm-high crate (17). A quadriceps machine (503291, Enraf-Nonius B.V., Rotterdam, The Netherlands) was used to perform the exercise, limiting the range of movement between 90 and 0° (0° = full extension of the knee). The exercise was performed with three levels of resistance, equivalent to 5, 10 and 15 % of the body weight (% BW) of each volunteer. The exercise was divided into three stages: i.- a concentric phase (90° to 0° extension); ii.- an isometric phase (holding the 0° position), and iii.- an excentric phase (0° to 90° flexion). The duration of each phase was 30, 10 and 30 seconds respectively, as shown in Figure 2.1C. Additionally, an electrogoniometer (Delsys, Boston, Massachusetts, USA) was installed between the thigh and leg segments to control the speed of execution of the concentric and excentric phases (3°/s). The recording of the electrogoniometer was superimposed over a predefined trapezoidal paradigm (Figure

2.1C). Both were shown to the volunteers in a monitor placed in front of them so that they received feedback of the position and speed of the knee in real time. Based on this, volunteers were asked to follow the established paradigm through the electrogoniometer, which led to all of them performing the exercise at the same speed.

HD-sEMG recordings

The EMG activity of the VMO and the VML was recorded with two-dimensional matrices of 32 surface electrodes (ELSCH064NM3, modified, OTBiolettronica, Torino, Italy). They were placed over the VMO and the VML such that the rows of electrodes were parallel to the muscle fibres. For this, two lines were drawn at angles of 47° and 15° from the longitudinal axis of the femur (the line between the mid part of the superior end of the patella and the anterior superior iliac spine, Figure 2.1A), for the VMO and the VML respectively (25). Before placing the electrodes, the skin was cleaned with an abrasive paste (Everi, Spes Medica s.r.l., Battipaglia, Italy) and washed with abundant water to diminish the impedance of the skin.

The EMG signals of each matrix were amplified in a simple differential mode with a gain of 2000 units in a bandwidth of 10-500 Hz. The EMG signals and the electrogoniometer were digitalised in a synchronised manner at a sampling frequency of 2048 Hz, with 12-bit resolution (EMG-USB2, OTBioelettronica, Torino, Italy).

Each volunteer performed at least three test repetitions for each resistance level in order to become familiar with the procedure. Then, the order in which the resistance (5, 10 and 15 % BW) was to be applied in the exercises was assigned by a simple randomisation. A five minute rest was considered between repetitions. Three repetitions of the exercise were performed for each resistance level.

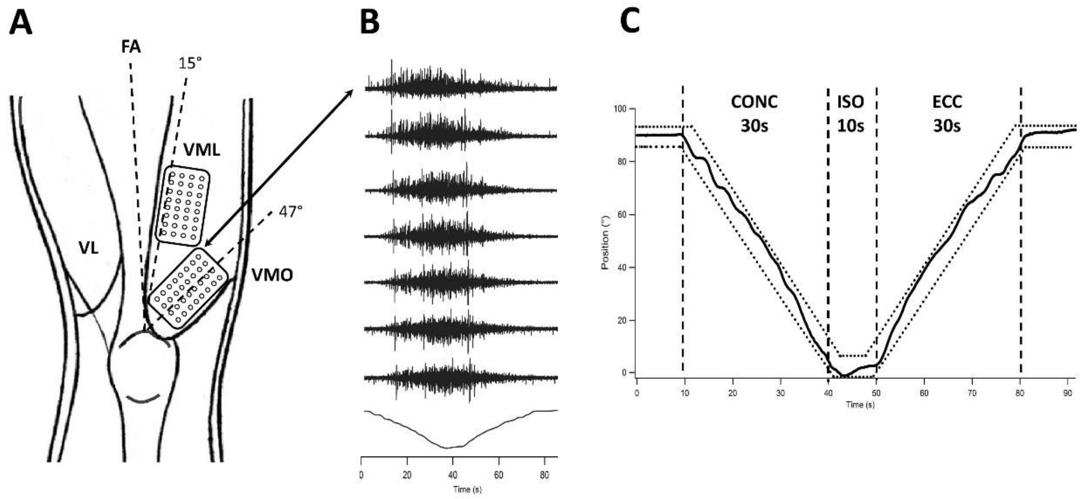

Figure 2.1. A: Localisation of the electrode matrices for the vastus medialis obliquus (VMO) and the vastus medialis longus (VML). B: Example of eight EMG signals of one of the rows of the matrix of the VMO and the recording of the electrogoniometer. C: Paradigm of the knee position to be followed with the electrogoniometer signal by the volunteer participants. Also shown here are the three phases of the exercise. CONC: concentric; ISO: isometric and ECC: excentric.

HD-sEMG data processing

In the analysis of the EMG signals the second repetition of each resistance level was considered. From both electrode matrices, 28 EMG signals were obtained for each component of the VM (VMO and VML). These signals were filtered digitally with a fourth order Butterworth type pass filter of 20-400 Hz. The analysis of the signals was performed considering the three phases of the exercise (concentric, isometric, and excentric), which were identified on the basis of the recording of the electrogoniometer (Figure 1C). To represent the activation of the MU of the VMO and the VML, the amplitude of the 28 signals of each matrix was calculated with the root mean square (RMS) using a window of 250 ms without overlap (5). To represent the level of activation of the VMO and the VML, the amplitudes of the 28 signals of each matrix were calculated. For example, for the 5 % BW resistance, the activation of the VMO in each phase of the exercise was given by: $VMO(5\%BW)_{Concentric} = \sum_{i=1}^{28} A_{RMS}(i)$; $VMO(5\%BW)_{Isometric} = \sum_{i=1}^{28} A_{RMS}(i)$ and $VMO(5\%BW)_{Excentric} = \sum_{i=1}^{28} A_{RMS}(i)$, where A_{RMS} represents the EMG amplitude of each signal recorded in the matrix corresponding to each component of the VM. All the analyses were done with a data processing software (IgorPro 6.2., WaveMetrics, Portland, OR, USA).

Statistical analyses

The data were initially subjected to a descriptive statistical analysis in which the Shapiro-Wilk test was applied to determine whether the data distribution fulfilled the assumption of normality. The comparisons between the VMO and the VML were done with a t-test. All the analyses were carried out with a statistical significance level of 95 % and one tail. The statistically significant differences were associated to a p-value of <0.05 (GraphPad 8v Software, San Diego, California, USA).

Results

The data revealed that the VMO generates a greater activation than the VML during the isometric phase with the three levels of resistance ($p<0.05$). Likewise, in the excentric phase, a greater activation was recorded for the VMO than for the VML in the 10 and 15 % BW resistance levels, while in the concentric phase the VMO showed greater activity than the VML only in the 15 % BW resistance level. Table 1 and Figure 2 show the activation levels of the VMO and the VML in the different phases and resistance levels.

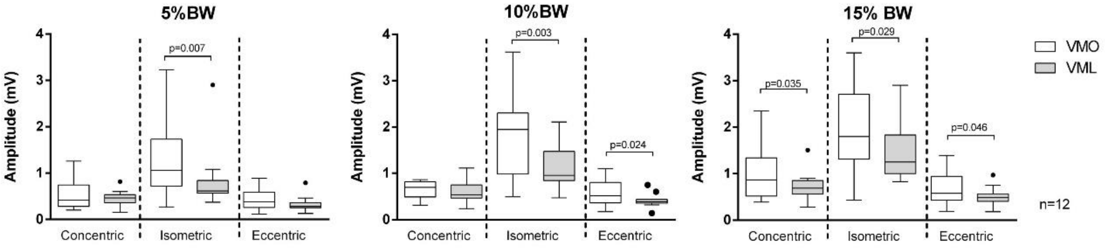

Figure 2.2. EMG amplitudes (mV) of the vastus medialis obliquus (VMO) and the vastus medialis longus (VML) during an open kinetic chain knee extension exercise, with three different levels of resistance (5, 10 and 15 % body weight [% BW]). Each level is analysed in its three phases: concentric (90-0°), isometric (0°), and excentric (0-90°). 0°: full extension of the knee (n=12).

Discussion

The results of this study show that the VMO has a greater activation level than the VML in the open kinetic chain flexion/extension exercise of the knee subjected to evaluation. This may show a functional difference between both components of the VM. These differences were identified in the isometric phase with all resistance levels. Similar findings have been reported by Hubbard and Opersteny (7) who, among several exercises, studied the EMG of the VMO and the VML during the maintained knee extension, similar to the isometric phase analysed in the present study. In contrast, Spairani et al. (21) reported a greater activation of the VMO than the VML in open and closed kinetic chain knee extension exercises. Differing from our study, these authors analysed static exercises focusing on the resistance of local muscle fatigue, based on the difference in the distribution of the type of muscle fibres between the VMO and the VML described by Rainoldi et al. (14). The discrepancy with our results may also be attributed to the characteristics of the matrices used in the study of Spairani et al., who used 4 electrodes (HD-sEMG) arranged in a single dimension, analysing only three signals to characterise the VMO vs. the VML, whereas in our study 28 signals were analysed for each component of the VM, implying that a larger number of MU were recorded during the exercises. Secondly, the levels of contraction appear to be important to determine the functional differentiation between the regions of a same muscle. In our study, the VMO showed greater activation than the VML with all levels of resistance for the isometric phase, while in the excentric phase the differences became evident from 10 % BW and for the concentric phase they were only observed with the 15 % BW resistance level. This shows that the differences in activation between the VMO and the VML are independent of the external resistance in the case of the isometric contraction whereas in the dynamic contractions said difference is dependent on the level of external resistance. This may indicate that the greater engagement of the VMO over the VML in dynamic conditions could be associated with a certain level of resistance and such differential activation would not be evident with either higher or lower resistance levels. In this context, prior studies in the superficial masseter muscle (5) have demonstrated the existence of a functional compartmentalization only at submaximal levels of isometric contractions (20-60 % MVC), while at higher percentages of the MVC this difference disappears. The resistance levels used in the present study were relatively low, which could have had an effect on the differences in activation between the VMO and the VML. The levels of external resistance used in this study were chosen on the basis of the recommendations provided in protocols of rehabilitation of the femoropatellar dysfunction in the acute and subacute phases (27, 28), where activation of the VMO is key.

One of the main novelties of the present study is the application of recording the VMO and VML muscle activity in the dynamic phases of the flexion/extension exercise of the knee. Our results show there is greater activation of the VMO than of the VML in the excentric phase (10-15 % BW) and the concentric phase (15 % BW only). These findings differ from those reported by Hubbard and Opersteny (7), who did not find significant differences in the level of activation between the VMO and the VML. Nevertheless, a recent study by Gallina et al. (4) supports our findings: they showed that, in young people, the nervous system is capable of activating different regions of the VM in a heterogeneous manner, providing a neuromuscular basis for the functional division of this muscle.

The functional or neuromuscular compartmentalization demonstrated in this work is consistent with that described in other skeletal muscles. Staudenmann et al. (23) recorded the differential activation of the different regions of the triceps surae in relation to movements of the foot and the direction of the force of reaction of the floor. Moreside et al. (13) demonstrated the existence of differential recruitment of the upper and lower portions of the rectus abdominis muscle in different exercises of low intensity. While studying the recruitment of different regions of the rectus femoris in exercises combining hip flexion and knee extension, Watanabe et al. (26) demonstrated the presence of at least two regions with differential recruitment.

One of the limitations of the present study is the precision in the alignment of the rows of electrodes in relation to the muscle fibers. This shortcoming could be addressed in future studies by ultrasonography during the procedure of positioning the matrix. However, given that in the present study only the amplitude of the EMG was analysed, said orientation is not crucial, unlike its influence in the determination of other EMG parameters such as the muscle fibre conduction velocity (3, 10, 15).

The results obtained in this study provide the basis to consider the feasibility of activation exercises that recruit the VMO in a more selective manner, as demonstrated in the isometric and exentric phases of the exercise analysed in this study. Future research should be designed to evaluate the effectiveness of the type of exercise analysed in this investigation in the rehabilitation and prevention of patellofemoral dysfunctions.

Conclusion

In the sample analysed, the EMG recordings describe a greater activation of the VMO when compared to the VML, this being more important in the isometric and excentric phases of the open kinetic chain flexion/extension of the knee. These findings suggest a functional compartmentalization of the VM.

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Capítulo III

Comparison of the electromyographic activity of different zones of the abductor digiti minimi muscle in search of a functional compartmentalization

INTRODUCTION

The *abductor digiti minimi* (ADM) muscle of the hand is the most superficial of the muscles of the hypothenar eminence. Its proximal insertion is found in the pisiform bone, in the *pisohamate* and *pisometacarpal* ligaments, as well as in the tendon of *flexor carpi ulnaris (17),* some authors include the *hamulus* process of the *hamatum* and the palmar carpal ligament. (7) to this insertion. It is distally inserted in the ulnar region of the first phalanx of the little finger and in the dorsal digital expansion (17), as well as in the dorsal expansion of the *extensor digiti minimi* muscle, the distal digital fascia and the skin at the level of the proximal interphalangeal joint (7, 21). The ADM is innervated by the deep motor branch of the ulnar nerve, which passes across the muscle at an average distance of 31mm, distal to the proximal edge of the pisiform. From a morphological point of view, it has been recognised that the ADM consists of a single fusiform belly (15, 23). However, more recent studies have more frequently shown the presence of two bellies, one medial and other lateral (4, 20), the latter being the most superficial (7). The action of the ADM involves abduction of the little finger and flexion of the metacarpophalangeal joint. Due to its proximity to the dorsal digital expansion, the ADM is a synergist muscle in the extension of the interphalangeal joint. In addition, this muscle plays an important role in grasping large objects when the fingers are extended (17). The action of the ADM, as a whole muscle, lies in the activation of its motor units (MUs). In this context, there are electromyographic (EMG) studies that demonstrate the existence of heterogeneity in the recruitment of MUs, which is dependent on their specific location within the muscle and on the characteristics of the motor task performed. This heterogeneity in activation has led to the hypothesis that certain muscles could be organised neuromuscularly as functional compartments (FC), beyond the existence that is demonstrable at a morphological level. This would imply that the MUs grouped in certain muscle regions would show different activation levels that differ from the MUs located in other zones of the same muscle (3). In this sense, several studies have demonstrated the existence of this neuromuscular compartmentalisation (NMC). Staudenmann et al.(22) recorded the differential activation of the different regions of the triceps surae, in relation to foot movements and the direction of the ground reaction force (GRF). Moreside et al (14) demonstrated the existence of differential recruitment of the upper and lower portions of the rectus abdominis muscle in different low intensity-exercises. While studying the recruitment of different regions of the rectus femoris in exercises combining hip flexion and knee extension, Watanabe et al. (24) demonstrated the presence of at least two regions with differential recruitment, so that two NMC were identified. Later, Guzmán-Venegas et al (8), demonstrated the existence of three FCs in the superficial masseter muscle during submaximal bite-force magnitudes. The relative large size, and the association with gross motor tasks are characteristic of the muscles that have been the subject of study in the search for their NMC. On the contrary, the intrinsic muscles of the hands have not been subject of studies in the search of possible NMCs, as these muscles are seen to be small and associated with quite fine tasks, implying that their motor units are relatively small (19). For this reason, it is of interest to test the hypothesis of the existence of possible FC in muscles with these characteristics. The objective of this study was to compare the activation of the MUs in different zones of the ADM in order to support the hypothesis of the existence of a FC in this muscle.

Material and method

By using a cross-sectional, analytical, observational study (10), a sample of 12 healthy volunteers (age 21 ± 1.6 years old; weight 75.3 ± 9.8 kg; height 176.2 ± 7.3 cm; average ± standard deviation) was evaluated. The following exclusion criteria were applied in the recruitment of volunteers: i.- history of musculoskeletal injuries to the upper limbs in the past 6 months (for example, fracture, muscle tear, sprain, etc.); ii.- history of both central and peripheral neurological conditions or diseases; iii.- consumption of substances such as alcohol and/or drugs in the previous 24 hours; iv.- habitual practice of sports that involve the use of the muscles of the hand (for example, climbing, judo, etc.); v.- use of psychotropic drugs in the past 6 months (e.g. olanzapine, risperidone, quetiapine, droperidol, clonazepam, sertraline, etc.). All volunteers gave written consent by signing an informed consent document. All procedures in this study were in accordance with the criteria of the Declaration of Helsinki and were approved by the local ethics committee (Date of approval: 2018-15-05 code: (SCEC201824).

Procedure

All assessments were performed in a laboratory environment. Each volunteer was asked to sit in a chair in front of a table, on which a specially designed device was placed to place the hand and part of his/her forearm (Figure 3.1A). Throughout the assessment, the elbow was kept in a 90 ° flexion position. In the device, a force sensor (3E151/014, Kinetecnics, Santiago, Chile) was installed to assess the isometric force developed by the ADM (Figura 1B). Likewise, the device allowed for the installation of a matrix of 64 surface EMG electrodes (ELSCH064NM5, OT Bioelettronica, Torino, Italy) which was arranged in 4 rows of 13 electrodes each, and one row of 12 electrodes (Figure 3.1C).This allowed us to record the electrical activity of the MUs in the different zones of the ADM. The electrode array was placed on the ADM, in a way that its rows were arranged parallel to the muscle fibres. In the first instance, the maximum voluntary isometric contraction (MVIC) of the ADM was assessed using the force sensor. Each volunteer was asked to perform three maximal contractions of the ADM, lasting four seconds, with one minute of rest between them. From these three recordings the maximum value was determined, and that was considered the MVC (8).

Prior to EMG recordings, the skin on the ADM was cleaned with an abrasive paste (Everei, Spes Medica, Battipaglia, Italy), in order to reduce the skin impedance. The recorded tests consisted of performing submaximal voluntary isometric contractions of the ADM, equivalent to 20, 40, 60 and 80% of the MVC, which were conducted following a pre-established paradigm (Figure 3.1D). The magnitude of the contractions was controlled by visual feedback from the ADM force record, which was superimposed over the paradigms, and both were graphed in real time on a screen located in front of the volunteer. There was a break of five minutes between each test, and their order of execution was randomly determined. Before the final recording, testing samples were carried out at 50% of the MVC in order to familiarise the volunteer with the procedure. The EMG signals were recorded using high-density EMG equipment (EMG-USB2, OT-Bioelettronica, Torino, Italy), and they were amplified in a monopolar manner with a gain factor of 500 units. The signals were digitised with a sampling frequency of 2048 hz in a bandwidth from 10 to 500 hz (8). A synchronised capture of both EMG and force sensor signals was made, which were stored using data collection software (OtBiolab version 2.6, OP Bioelettronica, Torino, Italy).

EMG signal processing

EMG data, corresponding to the central 5 seconds of each test (Figure 1D), were processed in order to consider data in a stable state. For the analysis of the signals, the outermost rows of the matrix were not considered in the analysis. Similarly, the most proximal and distal channels were not considered in the analysis. The foregoing was decided in order that the processed signals were found with greater certainty within the anatomical territory of the ADM. The 27 monopolar signals considered in the analysis were differentiated in the direction of the matrix rows (Z1, Z2 and Z3), thus, each row had 8 differential EMG signals (24 in total). Then, the amplitude of the signals was assessed calculated using the root mean square (RMS), using a 250 milliseconds window. Thus, for each signal, 20 RMS amplitude values were obtained corresponding to the 5 seconds of analysis. Therefore, for each row, a total of 160 RMS values were obtained. To represent the activity of the MUs of each row, and thus of the different regions of the ADM, the median of the 160 values was considered. The rows were assigned according to their location in the ADM, as follows: Z1: dorsal zone; Z2: dorsal-palmar zone, and Z3: palmar zone, as shown in Figure 3.1E.

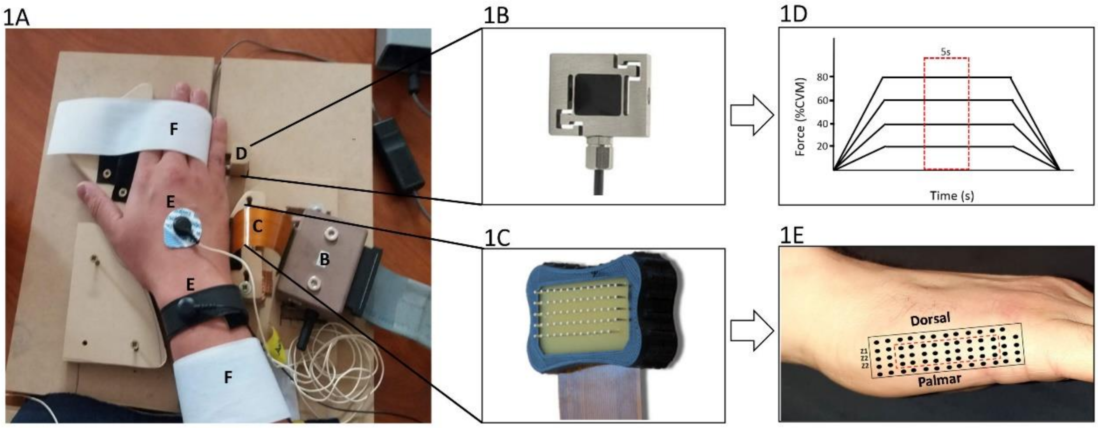

Figure 3.1. 1A: Set-up for measuring the activity of the motor units (MU) of the abductor digiti minimi (ADM) muscle. B: High-density electromyographic signal preamplifier. C: 64-electrode surface electromyography (sEMG) array. D: Force sensor. E: Reference electrode and cuff for electromyographic amplification. F: Velcro fastening for wrist and fingers. 1B: Force sensor used to measure the isometric force of the ADM. 1C: Detail of the arrangement of the 64 sEMG electrodes. 1D: Force paradigms performed by the volunteers at levels of 20, 40, 60 and 80% of maximum voluntary contraction (MVC). 1E: Location of the electrode array on the ADM. The zone has been highlighted with the red dashed line, and the electrodes that were used in the analysis of the MUs activity. The designation of recording zones are Z1: dorsal zone; Z2: dorsal-palmar zone and Z3: palmar zone.

Statistical analysis

Initially, a descriptive statistics analysis of the activation levels of the different zones of the ADM was carried out. The comparison of the activation levels of the MUs recorded in the different dorsal, dorsal-palmar and palmar zones (Z1, Z2 and Z3, respectively) was carried out through a mixed model analysis of covariance (12). All statistical analyses were carried out in two tails and with a statistical significance level of 95%. Statistically significant differences were those associated with a p-value <0.05. All analyses were performed using statistical analysis software (STATA/SE 12.1. Stata Corp. College Station, USA).

RESULTS

The EMG amplitudes recorded in the three zones of the ADM (Z1, Z2 and Z3) at the different contraction levels are shown as averages and standard deviation in Table 3.1. At the contraction levels of 20 and 60% MVC, no significant differences between the three zones were observed. At 40% MVC, the dorsal zone (Z1) showed greater activity than the palmar zone (Z3) (p = 0.039). Similarly, at 80% MVC, the dorsal zone showed greater activity than the dorsal-palmar zone (p = 0.037) and there was a tendency for the dorsal zone to have greater activity than the palmar zone (p = 0.053). P-values of all comparisons are presented in Table 3.2.

Table 3.1. Comparison of the normalised electromyographic amplitude between three zones (Z1, Z2 and Z3) of the *abductor digiti minimi* (ADM) muscle, during contractions at different levels. The amplitudes are shown as averages (standard deviation) of the EMG amplitude adjusted to the MVC.

%MVC	(Z1)	(Z2)	(Z3)	Inter-regional differences†
20%	27.1 (20.8)	24.4 (12.5)	23.0 (9.4)	None
40%	54.9 (31.7)	52.4 (30.6)	48.7 (22.0)	Z1>Z3†
60%	66.0 (22.7)	68.2 (25.9)	64.5 (15.9)	None
80%	94.6 (37.6)	78.3 (21.7)	79.5 (22.7)	Z1>Z2†

MVC: Maximum voluntary contraction.
† P-value< 0.05 in mixed model analysis.
Z1: dorsal zone; Z2: dorsal-palmar zone and Z3: palmar zone.

Table 3.2. P-values calculated from the comparison made using the mixed model analysis of covariance.

%MVC		(Z1)	(Z3)
20	(Z1)	**--**	0.224
	(Z2)	0.427	0.673
40	(Z1)	--	***0.039†***
	(Z2)	0.407	0.216
60	(Z1)	--	0.791
	(Z2)	0.716	0.530
80	(Z1)	--	0.053
	(Z2)	***0.037†***	0.881

MVC: Maximum voluntary contraction.
† P-value< 0.05 in mixed model analysis.
Z1: dorsal zone; Z2: dorsal-palmar zone and Z3: palmar zone.

DISCUSSION

The results of this research show that at certain levels of muscle contraction (40 and 80% MVC) the dorsal, dorsal-palmar and palmar zones of the ADM show differences in the recruitment of the MUs located in these zones, which could support the hypothesis of the existence of a functional or neuromuscular compartmentalisation of the ADM.

While it is true that the ADM has been the subject of previous electrophysiological studies (2, 6), to date, these studies have not focused on examining the heterogeneity in the recruitment of the MUs. The results of the present study bring to light the possible existence of a FC; however, the results are not categorical, since at certain levels of contraction (20 and 60% MVC), differences in the recruitment of MUs are not demonstrated. In this study, the activity of the MUs was examined, considering three zones: dorsal, dorsal-palmar and palmar (Z1, Z2 and Z3, respectively), which were divided according to the fusiform morphology of the ADM. From a mechanical perspective, it is difficult to justify the presence of differential activation of the MUs in different zones of a muscle whose fibres fusiformly converge to a single tendon. In comparison with another type of morphology —such as that of the masseter muscle—this turns out to be more justifiable, given that it has multiple insertion sites in the jaw, which suggests functional differences between the MUs of its different portions. Indeed, the existence of a FC has been evidenced in this muscle, using a fundamentally mechanical rationale (8). However, there is background information about muscles with a single tendon in which the behaviour of their MUs describes the existence of a FC. Blanksma & van Ejiden (1) demonstrated the heterogeneous recruitment of MUs from the *temporalis* muscle in humans during different chewing tasks. Furthermore, Wickham and Brown(25) showed the existence of a FC in the *pectoralis major* and *latissimus dorsi* muscles, in relation to different movements of the shoulder. Likewise, Méndez et al. (16), reported the existence of three functional compartments in the *fibularis longus* muscle.

The presence of the differential recruitment pattern between the three zones recorded in the ADM could have a morphological substrate related to the three motor branches emerging from the motor branch of the ulnar nerve that innervate the ADM (7). Possibly, each of these motor branches could innervate the muscle fibres located in the areas studied; however, the corroboration of this assumption should be done with histochemical and/or stereoscopic studies.

The differential recruitment of the MUs could be attributed to their different properties. It is well known that MUs have different metabolic and mechanical properties, which differentiate them in terms of size, rate of force production, resistance to fatigue and activation threshold, classifying them into fast, fast-slow and slow motor units (5, 13). In general, the fast MUs turn out to be large with a high activation threshold and low resistance to fatigue, while the slow ones are smaller in diameter with a low activation threshold, and they are more resistant to fatigue (9). On the other hand, it has been described that the distribution of the different types of MUs within a muscle proves to be heterogeneous, in which a greater amount of MU of a certain type is concentrated in certain regions (11, 18). For this reason, the differences in the activation levels of the MU of the three zones studied could be attributed to the heterogeneous distribution of the MU type within the ADM. The results indicate that the MUs located in the dorsal zone of the ADM showed greater activation than the MUs of the dorsal-palmar and palmar zones, being significant at 40 and 80% of the MVC. The foregoing could be interpreted as a higher concentration of slow MUs in this area, since this type of MU shows a lower activation threshold; however, this needs to be analysed by histochemical studies.

Within the limitations of this study is the fact of studying the activity of MUs of the ADM only in the main motor function of the ADM. Future research should consider, in addition to the abduction, the flexion component of the metacarpophalangeal joint, as well as functional tasks such as grasping.

CONCLUSION

The results obtained in the evaluated sample support the hypothesis of the existence of functional compartmentalisation in the ADM. However, further research is needed to determine with greater certainty the topographic behaviour of the MUs of the ADM.

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Capítulo IV

Discusión general

Los resultados de ambos estudios evidencian las diferencias en los niveles de activación de las UM ubicadas en distintas zonas de un mismo músculo, lo cual puede ser interpretado como una compartimentalización neuromuscular o funcional. Aquello resulta ser consistente con lo descrito en otros músculos esqueléticos. Staudenmann et al (18), quienes registraron las activación diferencial de las distintas regiones del *triceps surae*, en relación a los movimientos del pie y la dirección de la fuerza de reacción del piso. También, Moreside et al. (12) demostraron la existencia de un reclutamiento diferencial entre las porciones superiores e inferiores del recto abdominal, en distintos ejercicios de baja intensidad. Watanabe et al. (20) estudiando el reclutamiento de diferentes regiones del recto femoral, en ejercicios de combinación de flexión de cadera y extensión de rodilla, demostraron la presencia de por lo menos dos regiones con reclutamientos diferenciados. Paton & Brown (13) demostraron la activación diferencial de seis regiones distintas del pectoral mayor, durante la ejecución de diferentes movimientos de hombro. El autor de esta tesis también demostró la existencia de una compartimentalización funcional en el musculo masetero superficial(6, 7).

El reclutamiento diferencial de las UM, podría ser atribuido a las diferentes propiedades de estas. Es bien sabido que las UM presentan distintas propiedades metabólicas y mecánicas, que las diferencian en cuanto a su tamaño, tasa de producción de fuerza, resistencia a la fatiga y umbral de activación, clasificándolas en unidades motoras rápidas, rápidas-lentas y lentas (2, 11). De manera general, las UM rápidas, resultan ser de gran tamaño, de alto umbral de activación y baja resistencia a la fatiga, mientras que las lentas, son de menor diámetro, umbral de activación bajo y más resistentes a la fatiga (8). Por otro lado, se ha descrito que la distribución de los diferentes tipos de UM dentro de un músculo resulta ser heterogénea, concentrando en ciertas regiones una mayor cantidad de UM de un cierto tipo (10, 14). Existen antecedentes que plantean la idea que la distribución del tipo de fibras musculares en el interior de un músculo no es azarosa, sino más bien, tendría una distribución acorde a la funcionalidad específica de cada tipo de fibra muscular(3). Los desiguales niveles de activación de las UMs situadas en los diferentes sitios de registro de podrían estar relacionados con una especialización funcional de las UMs según la ubicación de estas al interior de un músculo(1). Esta especialización funcional puede estar relacionada con la distribución heterogénea del tipo de fibras musculares. En algunos músculos de mamíferos se ha observado que en algunas regiones, existe un mayor contenido de fibras musculares de tipo I, mientras que en otras una mayor concentración de más fibras de tipo IIa (16). Asociado a los anterior, los diferentes tipos de fibras, presentan diferentes umbrales de activación de UMs, basado en el principio de tamaño de Henneman (8). Este principio describe que el reclutamiento de las UMs durante el desarrollo de la fuerza muscular progresiva, describe un orden relacionado con el tamaño de las UMs. A bajos niveles de fuerza, se reclutan primero las pequeñas UMs (motoneuronas con somas pequeños con menos fibras musculares), mientras que las UMs más grandes (motoneuronas de grandes somas y mayor número de fibras musculares) son reclutadas posteriormente a medida que aumenta la demanda de fuerza. En la mayoría de los músculos esqueléticos, las UMs pequeñas tienen fibras de contracción lenta o fibras de tipo I, mientras que las UMs grandes están formadas por fibras de contracción rápida o fibras de tipo II (9). Una distribución heterogénea entre los porcentajes de fibras musculares al interior de VM o del ADM, no ha sido documenta. Sería de una gran contribución al conocimiento de la función muscular complementa estudios electrofisiológicos como el de esta tesis, con estudios histoquímicos que pudieran sustentar desde aquella perspectiva los hallazgos obtenidos. Existen estudio que han demostrado una mayor concentración de fibras tipo II por sobre el tipo I en el *Vastus lateralis* y VM(5, 15), sin embargo no existen antecedentes de las posibles diferencias entre la distribución de fibras entre el VMO y el VML. Sin embargo, el reclutamiento heterogéneo, también podría ser explicado por la capacidad del SNC para reclutar ciertos grupos de UMs de manera selectiva. Gallina et al.,(4) demostraron en personas jóvenes, que el sistema nervioso central es capaz de activar de manera heterogénea distintas regiones del VM, fundamentando desde la perspectiva neuromuscular la división funcional de este músculo.

Una justificación mecánica podría explicar la diferenciación en el reclutamiento de las UM del VML y VMO, dado la orientación de las fibras musculares de cada compartimento. Una explicación mecánica de este tipo ha sida dada para el hallazgo de la CF del músculo masetero superficial(6). Sin embargo, en el caso del ADM, todas las sus fibras presentan una dirección similar dada por su morfología fusiforme. Sin embargo, este músculo, presenta unidades motoras pequeñas que participan en general de tareas motoras finas(17)., lo cual podría hacer presumir que su organización funcional podría ser más compleja que la de grandes músculos con funciones más bien gruesas. Existen antecedentes que las unidades motoras ADM presentan una alta frecuencia de descarga, lo cual podría hacer presumir una alta concentración de fibras musculares tipo II (19). Sin embargo, no existen estudios histoquímicos que se hayan centrado en identificar la presencia de diferencias regionales en la distribución del tipo de fibras en este músculo.

El estudio de la función muscular desde la perspectiva de los compartimentos funcionales abre una novedosa preceptiva en el estudio de la función muscular, la cual podría ser muy útil en el diseño de ejercicios de activación específicos para ciertas porciones musculares que pudieran tener funciones específicas asociadas al tratamiento o prevenciones de lesiones musculoesqueléticas. También será posible identificar que compartimentos podrían tener mayor importancia en ciertas tareas motoras, y con ello, poder potencia la acción de estas, logrando quizás mejorar en rendimiento en dichas tareas motoras, ya sean funcionales, laborales o deportivas.

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Capítulo V

Conclusiones, aplicaciones prácticas y perspectivas futuras

Conclusión estudio I

En la muestra evaluada, los registros electromiogarficos describen una mayor activación del *Vastus Medialis Obliquus* en comparación al *Vastus Medialis Longus*, la cual es más importante en las fases isométricas y excéntricas de la flexión/extensión de rodilla en cadena cinética abierta. Estos hallazgos sugieren una compartimentalización funcional del *Vastus Medialis*.

Ampliación practica estudio I

Los hallazgos de este estudio entregan nueva información acerca del reclutamiento selectivo de los compartimentos funcionales del *Vastus Medialis*, lo cual podría ser aplicado al diseño de ejercicios que busquen mayor activación del *Vastus Medialis Obliquus* en el contexto de la prevención y/o tratamiento de la disfunción femoropatelar.

Perspectivas futuras estudio I

Futuras investigación pueden abordar otros tipos de ejercicio en búsqueda del reclutamiento selectivo de los comportamientos funcionales del *Vastus Medialis*. Por otro lado, determinar la eficacia de estos para el tratamiento de los síntomas asociados a la disfunción femoropatelar.

Conclusión estudio II

Los resultados obtenidos a partir de la muestra evaluada sostienen la hipótesis de una existencia de compartimentalización funcional del *Abductor Digiti Minimi*. Sin embargo, son necesarias más investigaciones para poder establecer con mayor claridad el comportamiento topográfico de las unidades motoras del *Abductor Digiti Minimi*.

Ampliación practica estudio I

Las aplicaciones prácticas de este estudio se enmarcan en la ciencia básica en cuanto al estudio de la estructura y función del músculo esquelético. Dado que pone en antecedentes que músculos pequeños asociados a funciones motoras finas también pueden contener una compartimentalización funcional. Dichos datos podrían ser útiles para el diseño y control de prótesis robotizadas, las cuales son accionadas por remantes musculares organizados en una compartimentalización funcional.

Perspectivas futuras estudio I

Futuras investigaciones, deben indagar con mayor profundidad en el estudio de la compartimentalización funcional de músculos asociados a funciones motoras finas, entregado así mayor información acerca de a organización funcional de estos y del reclutamientos de sus unidades motoras.

Capítulo VI

Artículos

Int. J. Morphol.,
39(1):205-210, 2021.

Neuromuscular Compartmentalization of the Vastus Medialis Muscle: Comparison of the Activity of the Vastus Medialis Obliquus and the Vastus Medialis Longus by High Density Electromyography

Compartimentación Neuromuscular del Músculo Vasto Medial: Comparación de la Actividad del Vasto Medial Oblicuo y del Vasto Medial Largo Mediante Electromiografía de Alta Densidad

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GUZMÁN-VENEGAS, R.; VALENCIA, O.; CADORE, E. & IZQUIERDO, M. Neuromuscular compartmentalization of the vastus medialis muscle: comparison of the activity of the vastus medialis obliquus and the vastus medialis longus by high density electromyography. *Int. J. Morphol., 39(1)*:205-210, 2021.

SUMMARY: Anatomical studies describe the vastus medialis (VM) as being subdivided into two morphologically distinct components, the vastus medialis obliquus (VMO) and the vastus medialis longus (VML). However, there are discrepancies regarding the functional differentiation of these components. The aim of this study was to compare the levels of activation of the VMO and the VML by high density surface electromyography. Twelve healthy young women (age: 21.4 ± 2.0 years; weight: 58.1 ± 7.5 kg; height: 1.6 ± 0.1 m), performed an open kinetic chain knee exercise during which the EMG activity of the VMO and the VML was recorded with two-dimensional matrices of 32 surface electrodes. The exercises were performed with three levels of resistance (5, 10 and 15 % of the body weight (BW)), considering three phases: concentric, isometric and excentric. In the isometric phase the VMO had greater activation than the VML with the three levels of resistance ($p<0.05$). In the excentric phase, the VMO also showed greater activation than the VML with the 10 and 15 % BW resistance levels, while in the concentric phase, the VMO showed greater activity than the VML with only the 15 % BW resistance. The results indicated significant differences in the activation level of the two components of the VM. This bears importance in the development of exercises intended to achieve a greater or more selective activation of the VMO. In the sample subjected to evaluation, the EMG recordings describe a greater activation of the VMO in comparison to the VML, which is more important in the isometric and excentric phases of the flexion/extension of the knee in an open kinetic chain. These findings suggest a functional compartmentalization of the VM.

KEY WORDS: Heterogeneous recruitment; Muscle activation pattern; Functional compartmentalization; Vastus medialis muscle.

INTRODUCTION

The vastus medialis muscle (VM) is one of the components of the quadriceps muscle, whose main function is the extension of the knee and which, in particular, has been attributed an active role in the medial stability of the patella (Waryasz & McDermott, 2008). Hence the clinical importance of its function in relation to the aetiology and treatment of patellofemoral dysfunction. This is one of the most prevalent knee pathologies in the young population, especially in women (Smith *et al*. 2018). The stabilizing role of the VM is mainly due to the orientation of its muscle fibres, the direction of which determines a medialising component of the patella (Waryasz & McDermott). Anatomical studies show there is a structural division of the VM into two elements, the vastus medialis obliquus (VMO) and the vastus medialis longus (VML) (Travnik *et al*. 1995; Smith *et al*. 2009; Rajput *et al*. 2017). The fibres of these components are oriented at 47° and 15° respectively from the longitudinal axis of the femur (Waryasz & McDermott). This morphologic characteristic leads to the presumption that each of these two components fulfils different functions, given the orientation of their lines

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of force (Blazevich *et al*., 2006). In this context, the VML has been attributed primarily a knee extensor role, while the VMO is the only active medial stabilizer of the patella (Speakman & Weisberg, 1977). Several studies have attempted to demonstrate the functional differences between these two components, nevertheless, their conclusions differ (Hubbard & Opersteny, 2002; Rainoldi *et al*., 2008; Spairani *et al*., 2012).

A possible explanation for this lies in the techniques used to obtain the EMG recordings. On the one hand, needle EMG involves taking an intramuscular recording with a reduced capture volume, reason for which its recordings involve a small number of motor units (MU) and thus its conclusions are limited to the activation of those few MU (Merletti & Parker, 2004; Merletti *et al*., 2008). This may be solved with bipolar surface EMG, a technique which involves a larger capture volume, incrementing in this way the number of MU it is capable of recording. However, in the case of large muscles, such as the VMO and the VML, the ratio between the capture volume and the muscle volume continues to imply that it leads to conclusions based on recording a reduced number of the total amount of MU.

In contrast to the above, high density surface EMG (HD-sEMG) (Masuda *et al*., 1983; Saitou *et al*., 2000; Farina *et al*., 2002; Merletti *et al*., 2008) is a technique that employs a greater amount of electrodes arranged in one- or two-dimensional matrices which cover a large surface of the muscle being studied and thus a greater capture volume. Hence, the conclusions obtained with this technique imply a large number of MU and, consequently, also imply results which are possibly closer to reality (Merletti & Parker).

The aim of this research was to compare the level of activation of the VMO to that of the VML in young women during a knee flexion/extension exercise using HD-sEMG to test the hypothesis that the VMO presents a greater level of activation than the VML, with the purpose of providing evidence of the functional or neuromuscular compartmentalization of the VM.

MATERIAL AND METHOD

A sample of 12 physically active young women (age: 21.4 ± 2.0 years; weight: 58.1 ± 7.5 kg; height: 1.6 ± 0.1 m) was evaluated in a cross sectional analytic observational study (Hernández & Fernández, 2014). The following exclusion criteria were applied when recruiting volunteer participants: i) history of pain or pathology of the knee within the last 12 months, ii) medical history of central or peripheral neurological diseases, iii) injury or infection of the skin over the VM muscle, iv) substance abuse (alcohol and/or drugs) in the 48 hours prior to the evaluation, v) having performed strenuous physical activity in the 48 hours prior to the measurement. All volunteers provided written agreement signing an informed consent document. The procedures in this study were in accordance with the criteria of the Declaration of Helsinki and were approved by the local ethics committee (SCEC201603, 07-03-2016).

Exercise. The EMG activity of the VMO and the VML was recorded during an open kinetic chain flexion/extension exercise of the knee. The recordings were performed on the dominant knee of each volunteer determined on the basis of the lower limb selected most frequently to descend from a 30 cm-high crate (Sadeghi *et al*., 2000). A quadriceps machine (503291, Enraf-Nonius B.V., Rotterdam, The Netherlands) was used to perform the exercise, limiting the range of movement between 90 and 0° (0° = full extension of the knee). The exercise was performed with three levels of resistance, equivalent to 5, 10 and 15 % of the body weight (% BW) of each volunteer. The exercise was divided into three stages: i.- a concentric phase (90° to 0° extension); ii.- an isometric phase (holding the 0° position), and iii.- an excentric phase (0° to 90° flexion).

The duration of each phase was 30, 10 and 30 seconds respectively, as shown in Figure 1. Additionally, an electrogoniometer (Delsys, Boston, Massachusetts, USA) was installed between the thigh and leg segments to control the speed of execution of the concentric and excentric phases (3°/s). The recording of the electrogoniometer was superimposed over a predefined trapezoidal paradigm (Fig. 1C). Both were shown to the volunteers in a monitor placed in front of them so that they received feedback of the position and speed of the knee in real time. Based on this, volunteers were asked to follow the established paradigm through the electrogoniometer, which led to all of them performing the exercise at the same speed.

HD-sEMG recordings. The EMG activity of the VMO and the VML was recorded with two-dimensional matrices of 32 surface electrodes (ELSCH064NM3, modified, OTBiolettronica, Torino, Italy). They were placed over the VMO and the VML such that the rows of electrodes were parallel to the muscle fibres. For this, two lines were drawn at angles of 47° and 15° from the longitudinal axis of the femur (the line between the mid part of the superior end of the patella and the anterior superior iliac spine, Fig. 1A), for the VMO and the VML respectively (Waryasz & McDermott). Before placing the electrodes, the skin was cleaned with an abrasive paste (Everi, Spes Medica s.r.l., Battipaglia, Italy) and washed with abundant water to diminish the impedance of the skin.

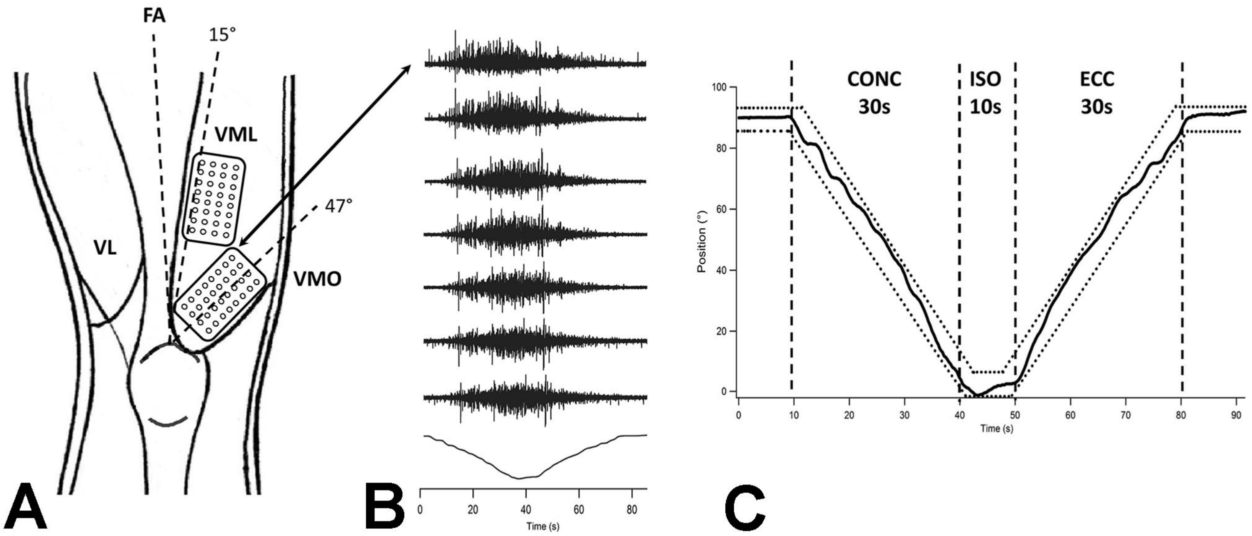

Fig. 1. A: Localisation of the electrode matrices for the vastus medialis obliquus (VMO) and the vastus medialis longus (VML). B: Example of eight EMG signals of one of the rows of the matrix of the VMO and the recording of the electrogoniometer. C: Paradigm of the knee position to be followed with the electrogoniometer signal by the volunteer participants. Also shown here are the three phases of the exercise. CONC: concentric; ISO: isometric and ECC: excentric.

The EMG signals of each matrix were amplified in a simple differential mode with a gain of 2000 units in a bandwidth of 10-500 Hz. The EMG signals and the electrogoniometer were digitalised in a synchronised manner at a sampling frequency of 2048 Hz, with 12-bit resolution (EMG-USB2, OTBioelettronica, Torino, Italy).

Each volunteer performed at least three test repetitions for each resistance level in order to become familiar with the procedure. Then, the order in which the resistance (5, 10 and 15 % BW) was to be applied in the exercises was assigned by a simple randomisation. A five minute rest was considered between repetitions. Three repetitions of the exercise were performed for each resistance level.

HD-sEMG data processing. In the analysis of the EMG signals the second repetition of each resistance level was considered. From both electrode matrices, 28 EMG signals were obtained for each component of the VM (VMO and VML). These signals were filtered digitally with a fourth order Butterworth type pass filter of 20-400 Hz. The analysis of the signals was performed considering the three phases of the exercise (concentric, isometric, and excentric), which were identified on the basis of the recording of the electrogoniometer (Fig. 1C). To represent the activation of the MU of the VMO and the VML, the amplitude of the 28 signals of each matrix was calculated with the root mean square (RMS) using a window of 250 ms without overlap (Guzmán-Venegas *et al*., 2015). To represent the level of activation of the VMO and the VML, the amplitudes of the 28 signals of each matrix were calculated. For example, for the 5 % BW resistance, the activation of the VMO in each phase of the exercise was given by: $VMO(5\ \%BW)_{Concentric} = \sum_{i=1}^{28} A_{RMS}(i)$; $VMO(5\ \%BW)_{Isometric} = \sum_{i=1}^{28} A_{RMS}(i)$ and , $VMO(5\ \%BW)_{Excentric} = \sum_{i=1}^{28} A_{RMS}(i)$ where ARMS represents the EMG amplitude of each signal recorded in the matrix corresponding to each component of the VM. All the analyses were done with a data processing software (IgorPro 6.2., WaveMetrics, Portland, OR, USA).

Statistical analyses. The data were initially subjected to a descriptive statistical analysis in which the Shapiro-Wilk test was applied to determine whether the data distribution fulfilled the assumption of normality. The comparisons between the VMO and the VML were done with a t-test. All the analyses were carried out with a statistical significance level of 95 % and one tail. The statistically significant differences were associated to a p-value of <0.05 (GraphPad 8v Software, San Diego, California, USA).

RESULTS

The data revealed that the VMO generates a greater activation than the VML during the isometric phase with the three levels of resistance (p<0.05). Likewise, in the excentric phase, a greater activation was recorded for the VMO than for the VML in the 10 and 15 % BW resistance levels, while in the concentric phase the VMO showed greater activity than the VML only in the 15 % BW resistance level. Table I and Figure 2 show the activation levels of the VMO and the VML in the different phases and resistance levels.

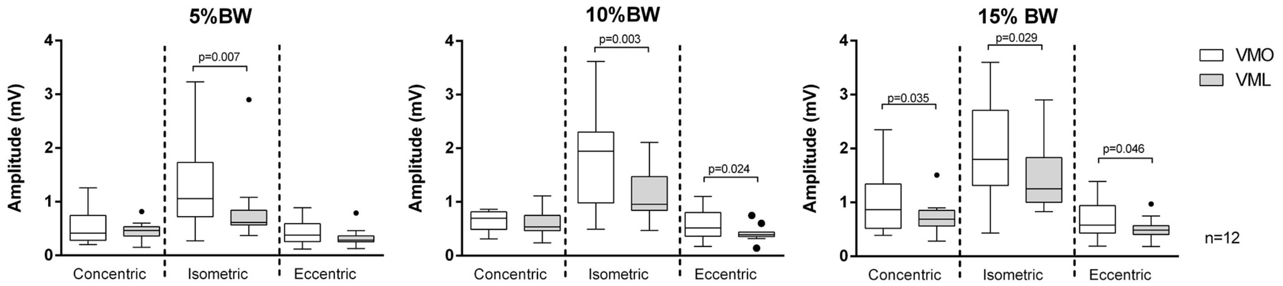

Fig. 2. EMG amplitudes (mV) of the vastus medialis obliquus (VMO) and the vastus medialis longus (VML) during an open kinetic chain knee extension exercise, with three different levels of resistance (5, 10 and 15 % body weight [% BW]). Each level is analysed in its three phases: concentric (90-0°), isometric (0°), and excentric (0-90°). 0°: full extension of the knee (n=12).

Table I. Amplitude sEMG of VMO and VML in young healthy women (n=12) during open chain flexion/extension knee exercise with different levels or resistance (5, 10 and 15%BW).

	5 %BW		10 %BW		15 %BW	
n=12	VMO	VML	VMO	VML	VMO	VML
Concentric (mV)	0.53(0.33)	0.46(0.16)	0.66(0.19)	0.61(0.26)	**1.00 (0.58)**^{d}	**0.72(0.30)**^{d}
Isometric (mV)	**1.25(0.78)**^{a}	**0.85(0.67)**^{a}	**1.77(0.90)**^{b}	**1.11(0.45)**^{b}	**2.03(0.95)**^{e}	**1.48(0.64)**^{e}
Excentric (mV)	0.43(0.24)	0.33(0.17)	**0.58(0.28)**^{c}	**0.42(0.15)**^{c}	**0.70(0.37)**^{f}	**0.51(0.20)**^{f}

%BW: percent of body weight; VMO: vastus medial oblique; VML: vastus medial longitudinal; mV: millivolts. ap=0.007; b=0.003; c=0.024; d=0.035; e=0.029; f=0.046

DISCUSSION

The results of this study show that the VMO has a greater activation level than the VML in the open kinetic chain flexion/extension exercise of the knee subjected to evaluation. This may show a functional difference between both components of the VM. These differences wereidentified in the isometric phase with all resistance levels. Similar findings have been reported by Hubbard & Opersteny who, among several exercises, studied the EMG of the VMO and the VML during the maintained knee extension, similar to the isometric phase analysed in the present study. In contrast, Spairani *et al*. reported a greater activation of the VMO than the VML in open and closed kinetic chain knee extension exercises. Differing from our study, these authors analysed static exercises focusing on the resistance of local muscle fatigue, based on the difference in the distribution of the type of muscle fibres between the VMO and the VML described by Rainoldi *et al*. (2008). The discrepancy with our results may also be attributed to the characteristics of the matrices used in the study of Spairani *et al*., who used 4 electrodes (HD-sEMG) arranged in a single dimension, analysing only three signals to characterise the VMO vs. the VML, whereas in our study 28 signals were analysed for each component of the VM, implying that a larger number of MU were recorded during the exercises. Secondly, the levels of contraction appear to be important to determine the functional differentiation between the regions of a same muscle. In our study, the VMO showed greater activation than the VML with all levels of resistance for the isometric phase, while in the excentric phase the differences became evident from 10 % BW and for the concentric phase they were only observed with the 15 % BW resistance level. This shows that the differences in activation between the VMO and the VML are independent of the external resistance in the case of the isometric contraction whereas in the dynamic contractions said difference is dependent on the level of external resistance. This may indicate that the greater engagement of the VMO over the VML in dynamic conditions could be associated with a certain level of resistance and such differential activation would not be evident with either higher or lower resistance levels. In this context, prior studies in the superficial masseter muscle (Guzmán-Venegas *et al.*) have demonstrated the existence of a functional compartmentalization only at submaximal levels of isometric contractions (20-60 % MVC), while at higher percentages of the MVC this difference disappears.

The resistance levels used in the present study were relatively low, which could have had an effect on the differences in activation between the VMO and the VML.

The levels of external resistance used in this study were chosen on the basis of the recommendations provided in protocols of rehabilitation of the femoropatellar dysfunction in the acute and subacute phases (Witvrouw *et al*., 2000, 2004), where activation of the VMO is key.

One of the main novelties of the present study is the application of recording the VMO and VML muscle activity in the dynamic phases of the flexion/extension exercise of the knee. Our results show there is greater activation of the VMO than of the VML in the excentric phase (10-15 % BW) and the concentric phase (15 % BW only). These findings differ from those reported by Hubbard & Opersteny, who did not find significant differences in the level of activation between the VMO and the VML. Nevertheless, a recent study by Gallina *et al*. (2017) supports our findings: they showed that, in young people, the nervous system is capable of activating different regions of the VM in a heterogeneous manner, providing a neuromuscular basis for the functional division of this muscle.

The functional or neuromuscular compartmentalization demonstrated in this work is consistent with that described in other skeletal muscles. Staudenmann *et al*. (2009) recorded the differential activation of the different regions of the triceps surae in relation to movements of the foot and the direction of the force of reaction of the floor. Moreside *et al*. (2008) demonstrated the existence of differential recruitment of the upper and lower portions of the rectus abdominis muscle in different exercises of low intensity. While studying the recruitment of different regions of the rectus femoris in exercises combining hip flexion and knee extension, Watanabe *et al*. (2012) demonstrated the presence of at least two regions with differential recruitment.

One of the limitations of the present study is the precision in the alignment of the rows of electrodes in relation to the muscle fibers. This shortcoming could be addressed in future studies by ultrasonography during the procedure of positioning the matrix. However, given that in the present study only the amplitude of the EMG was analysed, said orientation is not crucial, unlike its influence in the determination of other EMG parameters such as the muscle fibre conduction velocity (Rainoldi *et al*., 2000; Merletti *et al*., 2003; Farina *et al*., 2004).

The results obtained in this study provide the basis to consider the feasibility of activation exercises that recruit the VMO in a more selective manner, as demonstrated in the isometric and exentric phases of the exercise analysed in this study. Future research should be designed to evaluate the effectiveness of the type of exercise analysed in this investigation in the rehabilitation and prevention of patellofemoral dysfunctions.

CONCLUSION

In the sample analysed, the EMG recordings describe a greater activation of the VMO when compared to the VML, this being more important in the isometric and excentric phases of the open kinetic chain flexion/extension of the knee. These findings suggest a functional compartmentalization of the VM.

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GUZMÁN-VENEGAS, R.; VALENCIA, O.; CADORE, E. & IZQUIERDO, M. Compartimentación neuromuscular del músculo vasto medial: comparación de la actividad del vasto medial oblicuo y del vasto medial largo mediante electromiografía de alta densidad. *Int. J. Morphol., 39(1)*:205-210, 2021.

RESUMEN: Los estudios anatómicos describen que el músculo vasto medial (VM) se subdivide en dos componentes morfológicamente distintos, el vasto medial obliquus (VMO) y el vasto medial largo (VML). Sin embargo, existen discrepancias con respecto a la diferenciación funcional de estos componentes. El objetivo de este estudio fue comparar los niveles de activación del VMO y el VML mediante electromiografía de superficie de alta densidad. Doce mujeres jóvenes sanas (edad: 21,4 ± 2,0 años; peso: 58,1 ± 7,5 kg; altura: 1,6 ± 0,1 m), realizaron un ejercicio de rodilla de cadena cinética abierta durante el cual se registró la actividad EMG de la VMO y la VML con dos matrices dimensionales de 32 electrodos de superficie. Los ejercicios se realizaron con tres niveles de resistencia (5, 10 y 15% del peso corporal (PC)), considerando tres fases: concéntrica, isométrica y excéntrica. En la fase isométrica el VMO tuvo mayor activación que el VML con los tres niveles de resistencia (p <0,05). En la fase excéntrica, el VMO también mostró mayor activación que el VML con los niveles de resistencia de 10 y 15% BW, mientras que en la fase concéntrica, el VMO mostró mayor actividad que el VML con solo el 15 % de resistencia al BW. Los resultados indicaron diferencias significativas en el nivel de activación de los dos componentes de la VM. Esto tiene importancia en el desarrollo de ejercicios destinados a lograr una activación mayor o más selectiva del VMO. En la muestra sometida a evaluación, los registros EMG describen una mayor activación del VMO en comparación con el VML, que es más importante en las fases isométrica y excéntrica de la flexión / extensión de la rodilla en cadena cinética abierta. Estos hallazgos sugieren una compartimentación funcional de la VM.

PALABRAS CLAVES: Reclutamiento heterogéneo; Patrón de activación muscular; Compartimentación funcional; Músculo vasto medial.

GUZMÁN-VENEGAS, R.; VALENCIA, O.; CADORE, E. & IZQUIERDO, M. Neuromuscular compartmentalization of the vastus medialis muscle: comparison of the activity of the vastus medialis obliquus and the vastus medialis longus by high density electromyography. *Int. J. Morphol., 39(1)*:205-210, 2021.

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Title:

Comparison of the electromyographic activity of different zones of the *Abductor digiti minimi manus* muscle in search of a functional compartmentalisation.

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SUMMARY

There is evidence demonstrating the presence of functional compartmentalisation (FC) in some skeletal muscles. This means that the motor units (MU), grouped in certain areas of the muscle, show different levels of activation in comparison to those located in other zones. This has only been described in large muscles whose morphology proves the existence of a FC. However, there is no background information about small muscles, such as the *abductor digiti minimi manus* (ADM). The objective of this study was to compare the activation of the MU in different zones of the ADM to support the hypothesis of the existence of a FC in the ADM.

By using a cross-sectional, analytical, observational study, the activity of the MUs in the ADM was assessed in 12 volunteers (age 21 ± 1.6 years old; weight 75.3 ± 8 kg; height 176.2 ± 7.3 cm; average ± standard deviation).

The activity of MUs was evaluated using high-density surface electromyography (HD-sEMG) with an array of 64 electrodes arranged two-dimensionally. This allowed us to record the activity of the MUs in three zones of the ADM (Z1: dorsal zone; Z2: dorsal-palmar zone and Z3: palmar zone). Electromyographic recordings were obtained during voluntary isometric contractions of the ADM at 20, 40, 60 and 80 % of the maximum voluntary contraction (MVC). The comparison of the activation levels of MUs between the three zones was carried out using a mixed model analysis of covariance. The results showed a significant difference between the dorsal and palmar zones at 40 % of the MVC (p= 0.03), and between the dorsal and dorsal-palmar zone at 80 % of the MVC (p= 0.03). The results obtained in the evaluated sample support the hypothesis of the existence of FC in the ADM. However, further research is needed to determine with greater certainty the presence of this compartmentalisation in the ADM.

Key words: functional compartmentalisation, neuromuscular compartmentalisation; abductor digiti minimi manus, high-density surface electromyography.

RESUMEN.

Existe evidencia que demuestra la presencia de una compartimentalización funcional (CF) en algunos músculos esqueléticos. Aquello se traduce en que las unidades motoras (UM) agrupadas en ciertas zonas del músculo, presentan diferentes niveles de activación a las ubicadas en otras regiones. Esto solo ha sido descrito en músculos grandes, cuya morfología justifica la existencia de una CF. Sin embargo, no existen antecedentes de aquello en músculos pequeños, tales como el *abductor digiti minimi manus* (ADM). El objetivo de este estudio fue comparar la activación de las UM en distintas zonas del ADM, con la finalidad sostener la hipótesis de la existencia de una CF en el ADM.

Mediante un estudio observacional analítico transversal se evaluó la actividad de las UM del ADM en 12 voluntarios (edad 21 ± 1.6 años; peso 75.3 ± 8 kg; altura 176.2 ± 7.3 cm; promedio ± desviación estándar). La actividad de las UM, se evaluó mediante electromiografía de superficie alta densidad usando una matriz de 64 electrodos dispuestos bidimensionalmente. Esta permitió registrar la actividad de las UM en tres zonas del ADM (Z1: zona dorsal; Z2: zona dorso-palmar y Z3: zona palmar). Los registros electromiográficos fueron obtenidos durante contracciones isométricas voluntarias del ADM al 20, 40, 60 y 80 % de la contracción voluntaria máxima (CVM). La comparación de los niveles de activación de las UM entre las tres zonas fue realizada mediante un análisis de modelos mixtos de covarianza. Los resultados indicaron que existió diferencia significativa entre la zona dorsal y palmar al 40 % de la CVM ($p = 0.03$), y entre la zona dorsal y dorso-palmar al 80 % de la CVM ($p = 0.03$). Los resultados obtenidos en la muestra evaluada sostienen la hipótesis de la existencia de una CF en el ADM. Sin embargo, son necesarias más investigaciones para establecer con mayor certeza la presencia de esta compartimentalización en el ADM.

Palabras clave: compartimentalización funcional, compartimentalización neuromuscular; abductor digiti minimi, electromiografía de alta densidad.

INTRODUCTION

The *abductor digiti minimi of hand* (ADM) is the most superficial of the muscles of the hypothenar eminence. Its origin is found in the pisiform bone, in the *pisohamate* and *pisometacarpal* ligaments, as well as in the tendon of *flexor carpi ulnaris* (Palastanga *et al.*, 2002), some authors include the *hamulus* process of the *hamatum* and the palmar carpal ligament. (Gudemez *et al.*, 2002) to this insertion. It is distally inserted in the ulnar region of the first phalanx of the little finger and in the dorsal digital expansion (Palastanga *et al.*), as well as in the dorsal expansion of the *extensor digiti minimi* muscle, the distal digital fascia and the skin at the level of the proximal interphalangeal joint (Soldado-Carrera et al., 2000; Gudemez *et al*.).

The ADM is innervated by the deep motor branch of the ulnar nerve, which passes across the muscle at an average distance of 31mm, distal to the proximal edge of the pisiform. From a morphological point of view, it has been recognised that the ADM consists of a single fusiform belly (Testut & Latarjet, 1959; Murata *et al.*, 2004). However, more recent studies have more frequently shown the presence of two bellies, one medial and other lateral (Santo Neto et al., 1984; Buarque de Gusmão *et al.*, 2005), the latter being the most superficial (Gudemez *et al*.).

The action of the ADM involves abduction of the little finger and flexion of the metacarpophalangeal joint. Due to its proximity to the dorsal digital expansion, the ADM is a synergist muscle in the extension of the interphalangeal joint. In addition, this muscle plays an important role in grasping large objects when the fingers are extended (Palastanga *et al.*).

The action of the ADM, as a whole muscle, lies in the activation of its motor units (MUs). In this context, there are electromyographic (EMG) studies that demonstrate the existence of heterogeneity in the recruitment of MUs, which is dependent on their specific location within the muscle and on the characteristics of the motor task performed. This heterogeneity in activation has led to the hypothesis that certain muscles could be organised neuromuscularly as functional compartments (FC), beyond the existence that is demonstrable at a morphological level. This would imply that the MUs grouped in certain muscle regions would show different activation levels that differ from the MUs located in other zones of the same muscle (Brown *et al.*, 2007). In this sense, several studies have demonstrated the existence of this neuromuscular compartmentalisation (NMC). Staudenmann *et al.* (2009) recorded the differential activation of the different regions of the triceps surae, in relation to foot movements and the direction of the ground reaction force (GRF). Moreside *et al.* (2008) demonstrated the existence of differential recruitment of the upper and lower portions of the rectus abdominis muscle in different low intensity-exercises. While studying the recruitment of different regions of the rectus femoris in exercises combining hip flexion and knee extension, Watanabe *et al.* (2012) demonstrated the presence of at least two regions with differential recruitment, so that two NMC were identified. Later, Guzmán-Venegas *et al.* (2015) demonstrated the existence of three FCs in the superficial masseter muscle during submaximal bite-force magnitudes.

The relatively large size, and the association with gross motor tasks are characteristic of the muscles that have been the subject of study in the search for their NMC. On the contrary, the intrinsic muscles of the hands have not been subject of studies in the search of possible NMCs, as these muscles are seen to be small and associated with quite fine tasks, implying that their motor units are relatively small (Santo Neto *et al.*, 1998). For this reason, it is of interest to test the hypothesis of the existence of possible FC in muscles with these characteristics. The objective of this study was to compare the activation of the MUs in different zones of the ADM in order to support the hypothesis of the existence of a FC in this muscle.

MATERIAL AND METHOD

By using a cross-sectional, analytical, observational study (Hernández Sampieri et al., 2014), a sample of 12 healthy volunteers (age 21 ± 1.6 years old; weight 75.3 ± 9.8 kg; height 176.2 ± 7.3 cm; average ± standard deviation) was evaluated. The following exclusion criteria were applied in the recruitment of volunteers: i.- history of musculoskeletal injuries to the upper limbs in the past 6 months (for example, fracture, muscle tear, sprain, etc.); ii.- history of both central and peripheral neurological conditions or diseases; iii.- consumption of substances such as alcohol and/or drugs in the previous 24 hours; iv.- habitual practice of sports that involve the use of the muscles of the hand (for example, climbing, judo, etc.); v.- use of psychotropic drugs in the past 6 months (e.g. olanzapine, risperidone, quetiapine, droperidol, clonazepam, sertraline, etc.). All volunteers gave written consent by signing an informed consent document. All procedures in this study were in accordance with the criteria of the Declaration of Helsinki and were approved by the local ethics committee (Date of approval: 2018-15-05 code: SCEC201824).

Procedure

All assessments were performed in a laboratory environment. Each volunteer was asked to sit in a chair in front of a table, on which a specially designed device was placed to place the hand and part of his/her forearm (Fig. 1A). Throughout the assessment, the elbow was kept in a 90° flexion position. In the device, a force sensor (3E151/014, Kinetecnics, Santiago de Chile, Chile) was installed to assess the isometric force developed by the ADM (Fig. 1B). Likewise, the device allowed for the installation of a matrix of 64 surface EMG electrodes (ELSCH064NM5, OT Bioelettronica, Torino, Italy) which was arranged in 4 rows of 13 electrodes each, and one row of 12 electrodes (Fig. 1C).This allowed us to record the electrical activity of the MUs in the different zones of the ADM. The electrode array was placed on the ADM, in a way that its rows were arranged parallel to the muscle fibres. In the first instance, the maximum voluntary isometric contraction (MVIC) of the ADM was assessed using the force sensor. Each volunteer was asked to perform three maximal contractions of the ADM, lasting four seconds, with one minute of rest between them. From these three recordings the maximum value was determined, and that was considered the MVC (Guzmán-Venegas *et al.*).

Prior to EMG recordings, the skin on the ADM was cleaned with an abrasive paste (Everei, Spes Medica, Battipaglia, Italy), in order to reduce the skin impedance. The recorded tests consisted of performing submaximal voluntary isometric contractions of the ADM, equivalent to 20, 40, 60 and 80 % of the MVC, which were conducted following a pre-established paradigm (Fig. 1D). The magnitude of the contractions was controlled by visual feedback from the ADM force record, which was superimposed over the paradigms, and both were graphed in real time on a screen located in front of the volunteer. There was a break of five minutes between each test, and their order of execution was randomly determined. Before the final recording, testing samples were carried out at 50 % of the MVC in order to familiarise the volunteer with the procedure. The EMG signals were recorded using high-density EMG equipment (EMG-USB2, OT-Bioelettronica, Torino, Italy), and they were amplified in a monopolar manner with a gain factor of 500 units. The signals were digitised with a sampling frequency of 2048 hz in a bandwidth from 10 to 500 hz (Guzmán-Venegas *et al.*). A synchronised capture of both EMG and force sensor signals was made, which were stored using data collection software (OtBiolab version 2.6, OP Bioelettronica, Torino, Italy).

EMG signal processing

EMG data, corresponding to the central 5 seconds of each test (Fig. 1D), were processed in order to consider data in a stable state. For the analysis of the signals, the outermost rows of the matrix were not considered in the analysis. Similarly, the most proximal and distal channels were not considered in the analysis. The foregoing was decided in order that the processed signals were found with greater certainty within the anatomical territory of the ADM. The 27 monopolar signals considered in the analysis were differentiated in the direction of the matrix rows (Z1, Z2 and Z3), thus, each row had 8 differential EMG signals (24 in total). Then, the amplitude of the signals was assessed calculated using the root mean square (RMS), using a 250 milliseconds window. Thus, for each signal, 20 RMS amplitude values were obtained corresponding to the 5 seconds of analysis. Therefore, for each row, a total of 160 RMS values were obtained. To represent the activity of the MUs of each row, and thus of the different regions of the ADM, the median of the 160 values was considered. The rows were assigned according to their location in the ADM, as follows: Z1: dorsal zone; Z2: dorsal-palmar zone, and Z3: palmar zone, as shown in Figure 1E.

Statistical analysis

Initially, a descriptive statistics analysis of the activation levels of the different zones of the ADM was carried out. The comparison of the activation levels of the MUs recorded in the different dorsal, dorsal-palmar and palmar zones (Z1, Z2 and Z3, respectively) was carried out through a mixed model analysis of covariance (Littell *et al.*, 2006). All statistical analyses were carried out in two tails and with a statistical significance level of 95 %. Statistically significant differences were those associated with a p-value <0.05. All analyses were performed using statistical analysis software (STATA/SE 12.1. Stata Corp. College Station, USA).

RESULTS

The EMG amplitudes recorded in the three zones of the ADM (Z1, Z2 and Z3) at the different contraction levels are shown as averages and standard deviation in Table I. At the contraction levels of 20 and 60 % MVC, no significant differences between the three zones were observed. At 40 % MVC, the dorsal zone (Z1) showed greater activity than the palmar zone (Z3) ($p = 0.039$). Similarly, at 80 % MVC, the dorsal zone showed greater activity than the dorsal-palmar zone ($p = 0.037$) and there was a tendency for the dorsal zone to have greater activity than the palmar zone ($p = 0.053$). P-values of all comparisons are presented in Table II.

DISCUSSION

The results of this research show that at certain levels of muscle contraction (40 and 80 % MVC) the dorsal, dorsal-palmar and palmar zones of the ADM show differences in the recruitment of the MUs located in these zones, which could support the hypothesis of the existence of a functional or neuromuscular compartmentalisation of the ADM.

While it is true that the ADM has been the subject of previous electrophysiological studies (Farina *et al.*, 2008; Bouillard *et al.*, 2012), to date, these studies have not focused on examining the heterogeneity in the recruitment of the MUs. The results of the present study bring to light the possible existence of a FC; however, the results are not categorical, since at certain levels of contraction (20 and 60 % MVC), differences in the recruitment of MUs are not demonstrated. In this study, the activity of the MUs was examined, considering three zones: dorsal, dorsal-palmar and palmar (Z1, Z2 and Z3, respectively), which were divided according to the fusiform morphology of the ADM. From a mechanical perspective, it is difficult to justify the presence of differential activation of the MUs in different zones of a muscle whose fibres fusiformly converge to a single tendon. In comparison with another type of morphology —such as that of the masseter muscle— this turns out to be more justifiable, given that it has multiple insertion sites in the jaw, which suggests functional differences between the MUs of its different portions. Indeed, the existence of a FC has been evidenced in this muscle, using a fundamentally mechanical rationale (Guzmán-Venegas *et al.*). However, there is background information about muscles with a single tendon in which the behaviour of their MUs describes the existence of a FC. Blanksma *et al.* (1997) demonstrated the heterogeneous recruitment of MUs from the *temporalis* muscle in humans during different chewing tasks. Furthermore, Wickham & Brown (2012) showed the existence of a FC in the *pectoralis major* and *latissimus dorsi* muscles, in relation to different movements of the shoulder. Likewise, Méndez *et al.* (2013) reported the existence of three functional compartments in the *fibularis longus* muscle.

The presence of the differential recruitment pattern between the three zones recorded in the ADM could have a morphological substrate related to the three motor branches emerging from the motor branch of the ulnar nerve that innervate the ADM (Gudemez *et al.*). Possibly, each of these motor branches could innervate the muscle fibres located in the areas studied; however, the corroboration of this assumption should be done with histochemical and/or stereoscopic studies.

The differential recruitment of the MUs could be attributed to their different properties. It is well known that MUs have different metabolic and mechanical properties, which differentiate them in terms of size, rate of force production, resistance to fatigue and activation threshold, classifying them into fast, fast-slow and slow motor units (Burke *et al.*, 1971; McDonagh *et al.*, 1980). In general, the fast MUs turn out to be large with a high activation threshold and low resistance to fatigue, while the slow ones are smaller in diameter with a low activation threshold, and they are more resistant to fatigue (Henneman *et al.*, 1965). On the other hand, it has been described that the distribution of the different types of MUs within a muscle proves to be heterogeneous, in which a greater amount of MU of a certain type is concentrated in certain regions (Korfage & Van Eijden, 1999; Rainoldi *et al.*, 2000). For this reason, the differences in the activation levels of the MU of the three zones studied could be attributed to the heterogeneous distribution of the MU type within the ADM. The results indicate that the MUs located in the dorsal zone of the ADM showed greater activation than the MUs of the dorsal-palmar and palmar zones, being significant at 40 and 80 % of the MVC. The foregoing could be interpreted as a higher concentration of slow MUs in this area, since this type of MU shows a lower activation threshold; however, this needs to be analysed by histochemical studies.

Within the limitations of this study is the fact of studying the activity of MUs of the ADM only in the main motor function of the ADM. Future research should consider, in addition to the abduction, the flexion component of the metacarpophalangeal joint, as well as functional tasks such as grasping.

CONCLUSION

The results obtained in the evaluated sample support the hypothesis of the existence of functional compartmentalisation in the ADM. However, further research is needed to determine with greater certainty the topographic behaviour of the MUs of the ADM.

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Figure

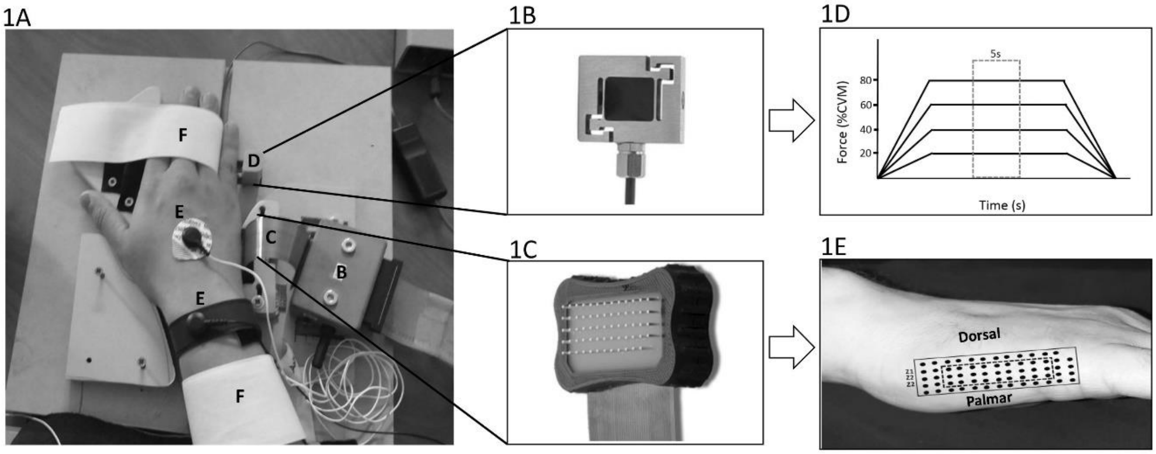

Fig. 1. Mounting details for electromyographic records of *abductor digiti minimi manus* (ADM). General view of set-up for measuring the activity of the motor units (MU) of ADM (1A), components of set-up: High-density electromyographic signal preamplifier(B). 64-electrode surface electromyography (sEMG) matrix (C). Force sensor(D). Reference electrode and cuff for electromyographic amplification(E). Velcro fastening for wrist and fingers (F).

Mounting sensors: force sensor used to measure the isometric force of the ADM (1B). Recording electrode matrix, (1C) detail of the arrangement of the 64 sEMG electrodes. Graph used to control the force of the ADM, (1D) force paradigms performed by the volunteers at levels of 20, 40, 60 and 80 % of maximum voluntary contraction (MVC). Location of the electrode array on the ADM (1E). The zone has been highlighted with the red dashed line, and the electrodes that were used in the analysis of the MUs activity. The designation of recording zones are Z1: dorsal zone; Z2: dorsal-palmar zone and Z3: palmar zone.