Techniques of Musculoskeletal System Imaging

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Abstract—Musculoskeletal models endow an opportunity to study the movement of the upper limb in vivo. The solid foundation of musculoskeletal model design is inherited from musculoskeletal parameters. Some of these parameters are tendon and muscle fiber length, pennation angle, and muscle volume. It is possible to extract these parameters based on cadaver. However, it is time-consuming and gives a generic statement about the function of the musculoskeletal system, but this is not enough to get accurate data and timely for each patient. Medical imaging has revolutionized visualization of the internal structure of the body in real time and in vivo. It is worth using medical imaging because it is impossible to imagine in real time what is inside the body unless surgery is performed; it is possible to see internal structure through cadaver dissection, but not in vivo. There are several kinds of medical imaging tools, which have been used in musculoskeletal system analysis such as Ultrasonography (US), Magnetic Resonance Imaging (MRI), Diffusion Tensor Imaging (DTI) and Computer Tomography (CT) scans. The work proposed aims to present principle, development and challenges of different medical imaging tools of musculoskeletal system methods. The outcomes of this paper show the choice of the imaging device for musculoskeletal system depends mainly on the motivation, target and the strong points that present in the medical imaging devices.

Keywords—musculoskeletal system, medical imaging, image analysis, MRI, DTI, CT, ultrasound

1 Introduction

Musculoskeletal modelling has received considerable attention by researchers because it gives a remarkable indication about how can analysis of muscle movement. Musculoskeletal modelling works as a non-invasive tool not only for movement analysis and prediction of the internal forces (reaction of muscles and bones), it also supports engineers in understanding the design of prosthetic devices. The solid foundation of musculoskeletal modelling is derived from measurement of morphological parameters of musculoskeletal system. This data was typically collected from cadavers, then assumed to represent typical individuals; therefore, this version of modelling is called generic musculoskeletal modelling [1],[2],[3].

One example of musculoskeletal models is upper limb model, which is shown in the Figure 1 [4]. It has been used in specific applications. Firstly, using the musculoskeletal model to understand the biomechanics of the muscle and joint loading on the upper extremity; where the musculoskeletal model was used in the examination of the joint coupling between the shoulder and the elbow [5],[6]. Also, it is used to assess the stabilising potential of the shoulder muscles [7]. Secondly, some musculoskeletal models were used to study and compare shoulder function among different activities, for example, hand cycling [8] and pushing a wheelchair [1]. Another objective of this model is analyzing the impact of the structural alteration on the shoulder function such as tendon transfer [9] and shoulder implants; this has supported designers in improving shoulder prosthesis [10]. Furthermore, recent musculoskeletal models were involved in developing the performance of the hand prosthesis in real time [11], and at real time estimation of mechanical properties of the upper extremity [12],[13].

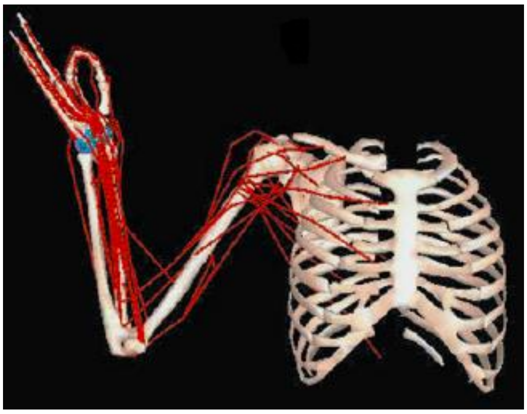

Fig. 1. Anterior view of musculoskeletal model of the upper extremity [4]

Two kinds of measurements are involved in the evaluation of the morphological parameters of the musculoskeletal system (muscle fibre length, tendon length and pennation angle). Firstly, a non-invasive quantitative measurement of the cadaver has been presented [2], [14], [15],[16]. As previously stated, generic musculoskeletal modelling is typically based on geometric parameters (muscle volume, tendon length, pennation angle) which are collected from cadavers [1],[2],[3]. The accuracy of cadaver data is restricted by several limitations such as preservation media, accurate dissection and in vitro; in vitro measurements are challenging due to the way of extrapolating and interpretation of the results [17], [18], [19]. The second measurement tool is medical imaging, it has revolutionized visualization of the internal structure of the body in real time and in vivo. It is powerful to imagine in real time what is inside the body without open and see. It is possible to see the internal structure through a cadaver dissection, but not in vivo. There are several kinds of medical imaging tools, which have been used in musculoskeletal system analysis such as US, MRI, DTI and CT scans. Researchers have intensified their experiences and information to develop medical imaging tools of musculoskeletal system. For example, using ultrasound imaging [18], [20]. and MRI in the identification of musculoskeletal parameters from a cadaver. Furthermore, combining the musculoskeletal model with MRI to determine moment arm and comparing it with experimental data [21] is used. The result shows the difference between the two measurements was reduced to 10% when combing MRI with musculoskeletal model. Medical imaging tools such as MRI, DTI and US are free from radiation and assist in the visualisation of the soft tissue rather than bone. Therefore, it is suitable for identifying the details of muscle and tendon. However, each modality has pros and cons in terms of the detail's recognition. For example, MRI is effective enough tool to depict muscle and tendon borders, but it does not provide a good enough view to describe muscle details [22], while the US does have potential for identification of muscle details such as fibre orientation [23]. DTI has a promising ability to recognise the direction of muscle fibre and could be a powerful modality [24], which will be used in the future for high-level visualisation of details in muscles and tendons. On the other hand, CT scans are a suitable choice for visualisation of bones rather than soft tissue, but it depends on radiation which has some restrictions on scanning.

Therefore, the rest of paper is organized to present principle, development and challenges of different medical imaging tools which have been used in the visualization of musculoskeletal system. Furthermore, comparison of different capabilities of these tools in the musculoskeletal imaging applications.

2 The Musculoskeletal System Imaging tools

There are different kinds of Musculoskeletal System Imaging tools. It is based on a particular physical principle and working on it requires different level of the expertise and skills.

2.1 Ultrasound imaging

Principle. Ultrasonography relies on transmissions of the ultrasound wave (frequency 1-20 MHz) through the body [25]. Some of these beams could be scattered as noise, while other beams could be converted to heat, which is absorbed by the body. The reflected beams are detected by an ultrasound probe or transducer, which translates the reflected signal into an image. Linear and curvilinear transducers are two familiar probes, which are used in musculoskeletal applications. The selection of a suitable probe depends on where the scan, size, and the depth of the musculoskeletal components are. In the case of scanning a superficial muscle, a linear probe is a preferable choice because the linear probe works with high frequency (7-20MHz). The low frequency< 7 MHz of a curvilinear probe is used to visualize the deep structure of the body [26].

There are three modes of the ultrasound machine scanning: A mode, B mode and M mode. A mode (amplitude mode) concerns with displaying the amplitude of an ultrasound signal, while B mode (brightness mode) displays the ultrasound echoes as bright dots to illustrate two-dimensional ultrasound image. Lastly, M mode is motion mode, which is used to analyze moving body parts such as cardiac and fatal cardiac imaging.

The ultrasound mode most commonly used in the visualization of musculoskeletal structure is B-mode [27, 28] because this mode translates the ultrasound echo of the musculoskeletal structure to two-dimensional ultrasound image.

Change in the angles of the ultrasound beam makes a massive difference on the fidelity of the image, for example, ultrasound images could be brighter than other images if the ultrasound beam was perpendicular to the tendon [29]. Therefore, holding a probe in the wrong way and not using adequate pressure during scanning will lead to inaccurate information [30]. If an angle between a probe and a skin is not perpendicular, this leads to produce artifact called anisotropy. This kind of artifact is direction dependent and commonly occurs in tendons due to the structural nature of the tendon which contains multiple, parallel linear interfaces (25]. However, to reduce the impact of the anisotropy, it is better to use a linear transducer because it has a higher possibility of being mostly perpendicular to the surface of the body.

The measurement of ultrasound imaging has inter-observer and intra-observer variability; inter-observer due to the different views in the measurement of the same scan region between different experts. The same expert could give a different view when scanning the same region at a different time, this is intra-observer. It is possible to avoid this variability and get an acceptable agreement regarding views by getting more practice on measurement protocols. Acoustic impedance is different from one tissue to another; it indicates the amount of echo, which is reflected from tissue depending on the density, for example, the acoustic impedance of the bone is larger than a muscle [31]. Consequently, the expertise is the main requirement to get a meticulous image and avoid some of the expected errors.

Development. Ultrasonography has become a more popular imaging modality than ever, patient has not need to expose to x-ray radiation or pass through magnetic. Furthermore, it is a cost-effective solution and portable as well. In addition, imaging via US machine is in real time, non-invasive and interestingly with dynamic and static scanning. Ultrasonography has been utilized in the medical applications for more than 70 years [32]. Indeed, Ultrasonography has had several applications in the musculoskeletal system during four decades of the development. In the first two decades, researchers concentrated their efforts in trying to solve issues related to musculoskeletal diseases, and analysis of which has an impact on muscle architecture. The first article, published in 1980 about the investigation of congenital dislocation in an infant hip [33]. The US was used as a supportive tool in observation of shoulder dislocation joint [34]. Furthermore, evaluation of the changes in the pennation angle of the brachialis muscle resulting from variation of the elbow joint angle and torque during a static and dynamic condition in vivo [35]. Perhaps, gravity has an impact on the measurement in the vertical or horizontal directions, Li &Tong executed the same experiment and found different results from Herbert due to this reason [36]. Then the changes of the moment arm were estimated for the Achilles tendon in the joint contraction and relaxation [37].

Perhaps, a comparison decade is a convenient term to describe the 2000’s decade because in this period researchers began to show the difference and similarities between different ways of measurements, different muscles and different sexes. Some of these applications are the comparison of morphological parameters of the muscles in the lower limb between cadavers and volunteers [18]. Experiments combining US and

Electromyography (EMG) measurements to extrapolate the influence on the muscle architecture during muscle contraction and rest have been done for the upper and lower limbs [38]. Appraisal of muscle size [39] and muscle mass was performed by US [40] as an alternative method instead of MRI. Prediction of muscle volume of the cadaver was made before dissection [41]. Furthermore, US estimation for morphological characteristics of extensor digitorium muscles to a group of male and female volunteers was performed, also force was measured to the same group and in the same time to illustrate the impact of the change of the muscle properties relative to the change of force [42].

The fourth decade is a motion decade; researchers have been interested in estimating tendon excursion and analysis of the mechanical properties of the tendon and muscle. Excursion of the finger tendon evaluated manually for cadaveric specimens and in vivo [43], described the relationship between stress and strain of the tendon in the lower limb [44]. Moreover, determination of the thickness of the lower trapezius muscle [45], and recognition of tendon and muscle tears is possible with dynamic imaging (imaging during movement) [46]. Estimating muscle morphological information using US of the rectus femoris and vastus lateral muscles in the lower limb before and after electrical stimulation was performed to observe the difference in the ultrasound images. [47].

Recently, Sonoelastography has emerged as a development of US to measure mechanical properties of the tendon tissue. It has several applications in the musculoskeletal system, for example, the effect of the change in the mechanical tendon properties on B-mode ultrasound intensity has been demonstrated in vitro [48]. A satisfactory estimation of the displacement and the strain of the tendon tissue has been achieved using two-dimensional Sonoelastography in vivo [49]. Although Sonoelastography has offered a new way to understand mechanical properties of the tendon tissue through the movement or musculoskeletal myopathy, it is still an inactive method in clinical utility [50]. Sonoelastography has several challenges, one of them is consuming time because it needs to measure a broad set of data; secondly, the results are nonlinear due to tendon tissue heterogeneity. Finally, the compression on the surface of the scanning might have a negative impact in focusing on the evaluation of the mechanical properties [48].

Challenge and limitations. The panoramic image added a new evolution in the ultrasound imaging applications because it presented ultrasound images in an ample view. Panoramic image is one of the imaging ways that reflects an integrated reality in one image by accumulating one view after another to appear whole details in the same image [51], [52]. They are a high similarity with CT scans in describing cross section details such as cross section of the quadriceps muscle [53] and gastrocnemius muscle [54]. Furthermore, it is approach to MRI abilities to describe some area of low limb muscles [55].

Although amenability of US has attracted patients and clinicians compared with other medical imaging devices, it still involves some challenges. Some of them have been addressed and others are still under research. US imaging has not had zero risks due to the presence of the thermal effect during visualization, although this is very low. Furthermore, calibration is necessary because the data is not the same in all US machines; mapping equations have been designed to apply the calibration between US machines [56].

Consequently, ultrasound imaging is a powerful option to extract musculoskeletal parameters automatically. Since, it is portable, flexible, cheap and interestingly provides high-level of the muscle details such as orientation of muscle fascicles.

2.2 Magnetic Resonance Imaging (MRI)

Principle. This modality which depends on the magnetic field and radio waves have made a quantum leap in the field of medical imaging. There are five main components of MRI, contributing with each other to achieve the work. The first one is a magnet that produces a static magnetic field; while the second is the magnetic gradient system (variant magnetic field). Radio frequency and coil system represent the third part; the resonance occurs between radio frequency and frequency of the selected region for imaging. Finally, the fourth and fifth parts are receiver and computer system respectively. The fundamental principle of MRI comes from the idea of polarization of hydrogen protons of water molecules; this means protons are arranged in parallel and antiparallel alignment under the effect of the magnetic field. Thus, the quality of the output image depends on the amount of water molecules in the body. Then, at resonance, protons are excited to store energy by moving it to antiparallel alignment instead of parallel alignment. In the relaxation stage, there are two essential parameters T1 (the time required for proton to go back into the previous position) and T2 (the lifetime of the echo signal), which have a huge impact on the image contrast. Proton Density (PD) is another contrast factor, which also has a clear imprint on the image contrast. The value of PD is varied based on the region of the body. In addition, selection of the thickness slice is critical because it has an enormous effect on the resolution [57].

Development. Many researchers are attracted to using MRI in the visualization of the musculoskeletal system, for it being renewed and an effective environment for research and development. The initial idea was introduced in 1971 [58] and then applied on the rat to detect tumors in 1974 [59]. Visualization of all of the human body was done in 1980. The MRI became three- dimensional (3D) in 1981, but it needed a lot of time to complete the scanning process [60]. After modification of 3D MRI by using parallel imaging, it was possible to use more flexible 3D MRI than previously. The first application of 3D MRI in the musculoskeletal system came after amendments in 1986, it was visualization a knee joint from volunteers and cadavers. The amendments focused on production a high-resolution of the image compared with the previous one [61]. In the same year, the first article was published about visualization regions in the upper extremity (hand and wrist), by passing a patient through a high strength magnetic field of 1.5 T [62]. Highlighting the capabilities of the magnetic resonance in the description of the muscles, joints, ligaments and tendons anatomically. MRI is a potential modality because it is effective in being able to browse anatomical structure and observe abnormality.

Regarding upper extremity, there are several applications; firstly, visualization of the anatomical structure of the shoulder [63] and the ability to differentiate between the normal shoulder and abnormal [64] were introduced. Secondly, illustrations of the anatomy of the elbow joint [65] and appraisal of the joint status by investigating the function ligament injuries were applied based on MRI [66]. Another application was a depiction of the muscles, ligaments and joints, which are related to wrist and hand [67]. Furthermore, MRI has a distinct role in recognition of the musculoskeletal diseases such as inflammation of the joints [68], [69]. In addition, MRI is valid in the observation of musculoskeletal diseases after treatment such as detection of Vitamin D deficiency because these diseases lead to changes in muscle architecture or muscle weakness, so it is possible to observe easily through imaging the cross section of the skeletal muscle [70]. MRI is a powerful tool in the analysis of the morphological properties of the muscle and tendon. Evaluation of the tendon length and moment arm values were achieved for three lower limb cadavers using MRI and a musculoskeletal model [71].

Challenge and limitation. One limitation of MRI imaging is dynamic MRI scanning, means imaging through movement. However, researchers have proposed and applied a developed version of MRI (dynamic MRI scan) such as kinematic MRI [72], real-time MRI [73] and cine phase-contrast MRI [74]. These kinds of MRI scan have some limitations The first type has the ability to detect some pathological conditions and photograph what happens during movement, but in a short time. As for the second type of dynamic MRI imaging, it is limited to one cycle and cannot cover all cycles of imaging. Therefore, in this case, it must be repeated in order for the whole imaging process to take place. However, not all patients have the ability to endure repetition in order to reach the desired result.

Another limitation of these types is the low image contrast. However, increasing the strength of the magnetic field can increase the contrast level, but again, not all patients can tolerate the increase in magnetic fields during the examination. Furthermore, it is expensive. [75]. Other limitations are associated with patients that have an implanted cardiac prostheses (pacemaker). It is important to be aware of this fact because it has a harmful effect on the patient [76]. The most important limitations of using MRI in the musculoskeletal visualization system are that it is time-consuming due to repetition; it might exhaust patients; especially elderly and disabled people and it is also expensive. However, automated methods for enhancement of MRI images can overcome this limitation to improve image contrast [77]. It is possible to be as powerful step to add this option to MRI machine.

2.3 Diffusion Tensor Imaging (DTI)

The main idea of the image construction using DTI is based on the understanding of motion and distribution of the hydrogen atoms in water molecules within soft tissue. The collision of the water molecules leads to diffusion; the diffusion is anisotropic because it is non-identical in all directions. If the image is constructed based on anisotropic diffusion, the contrast of the image will be increased; therefore, it is possible to tackle the contrast limitation of the MRI. There are three parameters to be considered in DTI structure. The first parameter is eigenvectors and eigenvalues, which describe the physical properties of the materials; for example, the largest eigenvector indicates the main diffusion direction, which corresponds to the fibre direction. The second one is Apparent Diffusion Coefficient (ADC) that illustrates the direction of the diffusion measurement; a bright image has high ADC. Lastly, FA (Fractional Anisotropy) describes the shape of the diffusion [78], [79].

There are several applications of using DTI in the musculoskeletal system: examining the validity of DTI in tracking skeletal muscle fibres at three dimensions for the animal leg [80] and human [81]. Tracking of muscle fibre illustrates a reasonable idea about fibres orientation, and this could be useful in observing the progress in musculoskeletal diseases. However, DTI is still as time-consuming as MRI even in tracking muscle fibres and it is expensive. Table 1, illustrates the comparison between three main medical imaging tools (US, MRI and DTI).

2.4 Computer Tomography (CT)

The Computerized Tomography (CT) is one of important tool in the visualization what it is inside of the body without open and see by surgery, basically this modality recruit’s x-radiation across a set of angles to get image slice then process it by computer [82]. So, it is possible to scan any section of the body as a serios of slices. Computerized tomography. CT is having a superior ability in the scanning hard tissue than MRI [83]. Since emerging COVID 19 epidemics, CT has a remarkable step in the diagnosis of the lung damage [84], [85]. It gives a picture of the COVID 19 impact on the lung and the level of development. However, the frequent use of this type of imaging tool has its risks due to the dose of radiation that the patient's body receives in each imaging session. If the patient takes a CT scan more than once in a short time, this leads to the accumulation of cells affected by each dose of radiation in his body, which leads to an increase in the possibility of developing cancer. In addition to the possibility of transmission of the virus infection from the Corona patient to the next person in the imaging room. Table 1 illustrates different medical imaging modalities with different properties.

Table 1. Comparison of different medical image tools

	MRI	DTI	US	CT
1	Expensive	Expensive	Cheap	Expensive
2	Non-portable	Non-portable	Portable	Non-portable
3	Static and very limited dynamic scanning	Static and very limited dynamic scanning	Static and dynamic scanning	Static and very limited dynamic scanning [82].
4	It has acceptable level of image contrast, but it is possible to improve it based on the hard or soft processing.	Has higher image contrast than MRI	Low image contrast and it has speckle noise	Has higher image contrast than MRI [83].
5	Time consuming	Time consuming	Flexible and not time consuming	Time consuming
6	Although it is free from radiation, it is very restricted to the people, who have metal inside a body such as a pacemaker. Furthermore, it is challenging to the people who, cannot cope with high level of magnetic field strength.	The same case of MRI.	Free from magnetic field and radiation. Furthermore, it is not restricted to any kind of implanted metal inside the body.	It has a high level of radiation and it is restricted for pregnant and patients who have some disease such as cancer.

7	It is possible to recognise muscles and tendons borders, but it is difficult to illustrate the details of the muscle architecture such as orientation of muscle fibres and pennation angles.	It has been involved to reconstruct the orientation of muscle fibres, but it still in early stage yet [24].	It is possible to present the borders of the muscles and tendons, also the details of the muscle architecture [20].	It is recommended for scanning a hard tissue such as bone [82].
8	It is not practical in case of the repetition because it is costly and may exhaust patients especially elderly and disable people [75].	The same case of MRI.	It is potential in the case of the repetition. However, an expert needs a considerable experience to avoid intraobserver variability.	It is not practical in case of the repetition because has a high level of radiation [85].

3 Analysis

Image analysis includes identifying the main parameters and properties of the image such as determining the colour properties of the different regions in the image, geometric evaluation of the properties of the object inside the image (area, diameter and length) and feature extraction of the image. Image analysis is the last stage in the image processing pipeline and could require pre-processing steps and tools particularly in the case of the analysis of medical images. For example, musculoskeletal ultrasound images need image enhancement to increase image quality by reducing speckle noise and raising the contrast of the regions [77], which have low contrast. Furthermore, sometimes segmentation or edge detection is a necessary step with image enhancement and works as a pre-processing step [77],[87]. Indeed, musculoskeletal ultrasound imaging analysis is more challenging compared with other medical images and other ultrasound images. This is due to the interaction between grey level intensities of the image; it is possible to detect pixels that have the same grey level intensities in the tendon and the muscle as an example. Several types of research have recently analysed the ultrasound imaging of the muscle and bones using digital image processing techniques. This is for determining geometric parameters, which describe the behaviour of the muscles, tendons and movement system automatically without biasing. Some of this work is evaluation of the pennation angle of gastrocnemius muscles [88] and vastus-lateralis in real time [89]; edge detection in this application was achieved as a pre-processing step using edge detection filters such as Canny edge detector, Sobel edge detector and Hough transform method. However, the superiority in the extraction of musculoskeletal parameters can be achieved by combining artificial intelligent tools with digital image processing techniques rather than only traditional processing tools. Therefore, this would help to improve the performance of the automatic approach and offer an array of benefits in terms of accuracy and speeding up the algorithms. One of recent example of geometric parameters extraction is automated evaluation of tendon cross section area and muscle fiber length [23],[90].

4 Conclusions

Every year, medical companies reveal more updates in medical imaging technologies and introduce the latest advanced devices and modern technologies. Currently, an ample range of medical imaging technologies are available that give ability for physicians to get a high level of accuracy of diagnosis such as MRI, X-ray machines and ultrasound machines. Medical equipment companies have benefited greatly from this technological development. This development is a cumulative product of a set of research that expands year after year to produce a qualitative leap in diagnosis and therefore treatment.

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