THE ACTION OF

BIARTICULAR MUSCLES

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Of course, we would also like to thank our families and friends for supporting us during times of stress and frustration.
Muscles are an essential part of the body, providing both stability and movement.

With amazing ease and grace, human beings are able to move around in the world and perform complex movement tasks. They do this with an action system consisting of numerous bones, joints and muscles (Bobbert, 1999).

Why are we interested in the functions of biarticular muscles? For scientists who are interested in unravelling the mysteries of human movement, there are two major questions: (1) Why is the action system built the way it is? And (2) why do people control their action system the way they do?

The first speculations on the functions of biarticular muscles arose more than 20 centuries ago. Aristotle already said that “nature created nothing without a purpose” (van Ingen Schenau, 1990). In other words, there must be a reason why the human body is equipped with so many bi- and polyarticular muscles and does not only consist of monoarticular ones. One may assume that particular design aspects and properties of the human action system have been selected in evolution because they allow for more efficient solutions to movement problems (Bobbert, 1999).

However, since any combination of net joint moments can theoretically be achieved by sets of monoarticular muscles, it is not obvious to what extent biarticular muscles might have a unique function which could not be performed by sets of monoarticular muscles. This notion is also reflected by the description of muscles found in textbooks of functional anatomy where biarticular muscles are treated as if they function as two monoarticular muscles (Paul et al., 1994).

Between 1850 and 1950 various studies were published suggesting that biarticular muscles are able to perform unique actions which cannot be performed by two monoarticular muscles crossing the same two joints (van Ingen Schenau, 1990). Since then a lot of research has been carried out with the aim of revealing the purpose and functions of biarticular muscles.

The question about the purpose and the function of two-joint muscles belongs to the field of coordination. The principle of muscle redundancy (van Ingen Schenau, 1989; Zhang et al., 1998; Prilutsky, 2000; Bobbert, 2000) means that the number of muscles crossing one joint generally exceeds the degrees of freedom of this particular joint (Zhang et al., 2000). For example, at least five muscles can contribute to flexion torque in the elbow joint. Therefore, multiple muscle activation patterns are theoretically possible in order to achieve this flexion torque.

Nevertheless, studies on activation patterns have shown that for a given motor task more or less the same activation patterns occur among different subjects (Bobbert et al., 1988; Doorenbosch et al., 1995; Theeuwen et al., 1996; van Bolhuis et al., 1997). This suggests that the central command continuously activates the same muscles in the same order for a given task and raises the question, why the central command always chooses the same specific pattern despite an infinite number of possible variations.

The observation of a more or less unique activation pattern for different motor tasks suggests the existence of underlying constraints, reducing the number of possible activation
patterns for each task (van Bolhuis et al., 1998).

It is hypothesized that the given patterns are a product of evolution, as is our central command and the effectors organs (Bobbert, 2000). This suggests that there must be a reason for the design of the human locomotor system, for our central command as well as for the product of the two, meaning the given stereotypical patterns of muscle activation for a given task or movement. When looking at the human body from a mechanical point of view one must assume that there is a reason and an advantage of a locomotor system which contains both mono- and biarticular muscles compared to a system which is only equipped with one-joint muscles (Bobbert, 2000).

Understanding the exact functions and mechanisms of two-joint muscles is not only important within the scientific field. Also for those who apply their anatomical and biomechanical knowledge to other people, such as physiotherapists, this knowledge can be of major advantage. Working with the human musculoskeletal system makes up a major part of physiotherapeutic reality. It is therefore essential for physiotherapists to know the exact functions of muscles. How could one otherwise develop good exercises for a patient without being familiar with the exact roles of muscles during certain movements?

According to our knowledge, no approach has been aimed at applying this important but rather complex knowledge to physiotherapeutic reality and to find means of integrating it into the treatment of patients with musculoskeletal disorders.

The aim of the current review is threefold and we therefore formulated the following research questions:
(1) What is the current knowledge on the functions of biarticular muscles? This includes giving additional anatomical and biomechanical information that is necessary to comprehend the contents of the paper.
(2) Do biarticular muscles have unique functions compared to monoarticular muscles?
(3) Can these findings of current scientific literature on the functions of biarticular muscles be applied to practical examples in the field of physiotherapy?
METHODS

A literature search was conducted using PUBMED (1988-2004), ELSEVIER, PEDRO and GOOGLE with the keywords “biarticular muscles”, “two-joint muscles”, “coordination”, “energy transfer” and “van Ingen Schenau”. We included only peer-reviewed journal articles, which were either descriptive or experimental in design; review articles were also included in our analysis.

Exclusion criteria:

All articles were excluded which were published before 1988 as well as poor quality articles as was determined by our criteria list and studies which were not performed on human beings. In our review we include articles as far back as 1988 as a lot of research had been carried out on biarticular muscles at that time and are frequently referred to by many current research studies. We regard the findings of these not so current research studies as making a substantial contribution to the current knowledge on biarticular muscles as they were the ones who actually got the discussion going.

Evaluation of literature:

Both reviewers evaluated all of the topic related articles by means of a criteria list. This criteria list is based on the “Quality criteria for medical informatics research papers” (version 2002) from the Yearbook of Medical Informatics from the university of Heidelberg (http://www.med.uni-heidelberg.de/mi/yearbook/quality_criteria.pdf) and was slightly adjusted to suit the field of physiotherapy.

A score was given ranging between 0 and 100%. All articles scoring more than 66% of the maximum score are of sufficient quality and are therefore included in the present review. The criteria list enables articles to be judged differently depending on their study design. Each point of the criteria list is scored with either 1 = full correspondence, 0,5 = partial correspondence or 0 = no correspondence.

All articles were read and evaluated by both group members. When the scores given by both reviewers deviated by more than 5% the specific article was discussed and a final score was agreed upon. For deviations of 5% or less the average of both scores was taken as the final value. See also 9.3 of the appendix for a full version of the criteria list.

In 8.2 of the appendix we introduce and discuss the most commonly used methods of the studies we have reviewed.
Chapter I

Applied Anatomy
1.1 TERMINOLOGY AND DEFINITIONS

This chapter gives an overview of certain anatomical and biomechanical items which are related to the topic of the current review. Perhaps you are already familiar with one or the other item of this chapter; nevertheless, its contents are essential for the rest of the paper. One can picture it as the ‘roots of a tree’, forming the basic fundament of this paper. The following chapters build upon this fundamental knowledge, therefore representing the ‘branches and leaves’ of the tree.

The muscles

The names of many muscles occur in the current paper. To make it easier on the reader we will give an overview of all the relevant muscles and their abbreviations as they occur in the paper (Table1).

Table 1. List of muscles and their abbreviations

<table>
<thead>
<tr>
<th>Extremity</th>
<th>MA vs. BA</th>
<th>Abbreviation</th>
<th>Full name</th>
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<tbody>
<tr>
<td>Upper</td>
<td>Monoarticular</td>
<td>DEL p. st.</td>
<td>Deltoid pars sternalis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DEL p. cl</td>
<td>Deltoid pars clavicularis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DEL p. sp.</td>
<td>Deltoid pars spinata</td>
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<tr>
<td></td>
<td></td>
<td>COR</td>
<td>Coracobrachialis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INF</td>
<td>Infraspinatus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TMJ</td>
<td>Teres major</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PEC</td>
<td>Pectoralis major</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BRD</td>
<td>Brachioradialis</td>
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<tr>
<td></td>
<td></td>
<td>BRA</td>
<td>Brachialis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TLA</td>
<td>Triceps brachii lateralis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ANC</td>
<td>Anconeus</td>
</tr>
<tr>
<td>Lower</td>
<td>Biarticular</td>
<td>BIB</td>
<td>Biceps brachii (both heads)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TLO</td>
<td>Triceps longus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EDI</td>
<td>Extensor digitorum</td>
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<tr>
<td></td>
<td></td>
<td>FCR</td>
<td>Flexor carpi radialis</td>
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<tr>
<td>Monoarticular</td>
<td>IL</td>
<td>GU</td>
<td>Iliopsoas</td>
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<tr>
<td></td>
<td>VAS</td>
<td></td>
<td>Gluteus maximus</td>
</tr>
<tr>
<td></td>
<td>VL</td>
<td>VM</td>
<td>Vasti (lat. and med.)</td>
</tr>
<tr>
<td></td>
<td>TA</td>
<td>SOL</td>
<td>- Vastus lateralis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Vastus medialis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tibialis anterior</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Soleus</td>
</tr>
<tr>
<td>Biarticular</td>
<td>HA</td>
<td>ST</td>
<td>Hamstrings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SM</td>
<td>- Semitendinosus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BF</td>
<td>- Semimembranosus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RF</td>
<td>- Biceps femoris (caput longum)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GA</td>
<td>Rectus femoris</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gastrocnemius</td>
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Biomechanical models

a) Lower extremity

In the search for an answer concerning the action system and its control it is, of course essential to collect kinematic, kinetic and electromyographic (EMG) information during movements. Analysis of this information may lead to the development of theories and the formulation of hypotheses.

Unfortunately, most of these hypotheses can not be tested experimentally on human subjects. After all, human subjects have a given anatomy and are unable to change their muscle stimulation patterns according to the experimenter’s desires (Bobbert, 1999). For ethical reasons, also, it is hardly possible to do “in vivo” studies of the musculoskeletal system. For example intramuscular EMG gives more accurate information on muscular activity, but as it involves implanting the electrodes in the muscle this method is rather unpopular when doing research on human beings.

Besides that, many crucial variables, such as muscle forces can not be measured directly. Due to these limitations in experimental research, researchers favour computer simulation methods in order to analyze certain movements (Bobbert, 1999).

Below, we will describe a computer model which commonly occurred in the reviewed literature and which we will also make use of, in order to explain certain biomechanical aspects.

Therefore it is necessary to make use of (computer-) models in order to be able to analyze movements of the human body. The following, so called “4-linked rigid segments model”, frequently occurs in scientific literature and is also used in the present study to explain certain biomechanical items concerning the function of biarticular muscles.

This model consists of the following components:

- It contains four linked-rigid segments; the head, arms and trunk (HAT) which are fused to form one segment while the rest of the body is divided into thigh, shank and foot (Fig. 1).
- All of the segments are connected by hinge joints with one degree of freedom; the whole model therefore only represents movements performed in the sagittal plane.
- The axes of the joints are located in the joint centre.
- It is assumed that there is no loss of energy through friction in the joints and gravity and ground reaction forces are neglected.
- The segments of the body are connected with muscles (Table 1).
- Each muscle is modelled as a Hill-type unit consisting of a contractile element (CE), a series elastic element (SEE) and a parallel elastic element (PEE).

Depending on the movement which is analyzed, it is not always necessary to show all 4 segments; in that case only those segments are shown which are of interest for that particular task.
How can one test whether the model adequately represents the ‘real’ human body? A suitable way to evaluate the model used in the study is to compare the movement of the model with that of a human subject. If the movement patterns established by means of the model correspond with that of the human subject, then it may be concluded that the model indeed represents the important features of the real system (Bobbert, 1999).

b) Upper extremity

As we frequently talk about studies about the upper extremity we will introduce another model. The model is used to analyse certain movements of the upper extremity, fig. 2 shows the model in the transversal plane.

Fig. 1 Linked-segments model of the lower extremity and trunk. The yellow circles indicate the joints, while the blue rectangles show the segments. The most important bi- and monoarticular muscles are shown with their abbreviations.
The model consists of the following components:

- It contains three linked rigid segments, the trunk, upper arm and forearm. The hand is neglected as we do not deal with muscles which cross the joints of the hand.
- All of the segments are connected by hinge joints with one degree of freedom; the whole model therefore only represents movements performed in the transversal plane. The forearm is in neutral position between pro- and supination; the shoulder is in 90° flexion and internal rotation.
- The axes of the joints are located in the joint centre.
- It is assumed that there is no loss of energy through friction of the joints and gravity and ground reaction forces are neglected.
- The segments of the body are connected with muscles (Table 1).
- Each muscle is modelled as a Hill-type unit consisting of a contractile element (CE), a series elastic element (SEE) and a parallel elastic element (PEE).

Length-tension relationships

The ideal length-tension relationship with a sarcomere occurs when a muscle is slightly stretched and the actin and myosin filaments barely overlap (Fig. 3). This permits sliding along nearly the entire length of the actin filaments. In this state, the contractile components are able to produce optimal tension while the passive components, parallel elastic component (PEC) and series elastic component (SEC), are able to store elastic energy, therefore adding to the total tension in the unit (Hamill et al., 1995). The effect of this can be seen in many daily activities, such as the push-off during jumping, where 25% of the ankle force results from releasing the energy that was stored in the tendon of the triceps surae. There is a relation between length of a muscle and the tension developed, this is illustrated in Fig. 4.

Fig. 3 shows the length-force diagram of a muscle. The x-axis represents the length of the sarcomere while the y-axis shows the force developed by the muscle at the particular sarcomere length.
Fig. 4 shows the length-tension diagram. It expresses the interaction between the contractile and elastic elements of a muscle fibre. The x-axis represents the length of the sarcomeres while the y-axis shows the isometric tension developed by the muscle. Both the contractile elements of a muscle as well as the passive components are shown; these consist of the series elastic component (SEC) and the parallel elastic component (PEC). $L_0$ represents the optimal length of the sarcomere (Source: Hamill et al., 1995).

When **lengthening** a muscle beyond its optimal length (resting length) the tension generated by a muscle will decrease. This is due to a slippage of the cross-bridges which results in a decreased formation of cross-bridges (Fig. 5 bottom).

Fig. 5 shows different sarcomere lengths: at the top the sarcomere length is 2.7 $\mu$m (muscle shortening), while at the bottom it is 4 $\mu$m (muscle lengthening).

At the opposite extreme, when **shortening** a muscle, the sarcomeres are so compressed that the Z-lines about the myosin myofilaments and the actin filaments touch and interfere with each another (Fig. 5 top). Under these conditions only little further shortening can occur (Marieb, 1992).

Thus, at the end of a joint movement or range of motion of a segment, the muscle is weak and incapable of generating large amounts of force due to its shortened length (Hamill et al., 1995).
Force-velocity relationships for concentric and eccentric muscle actions

a) Concentric muscle action:

The velocity of a concentrically active muscle is increased at the expense of a decrease in force, and vice versa. The maximum force can be generated at a velocity of zero, and the maximum velocity can be achieved with the lightest load. An optimal force can be achieved at zero velocity as a large number of cross-bridges are attached. As the muscle shortening velocity increases, the cycling rate of the cross-bridges increases, leaving fewer cross-bridges attached at one time. This leads to less force, and at high velocities, when all the cross-bridges are cycling, the force production is negligible. This relationship is shown in the right half of Fig. 6.

![Force-velocity relationship for concentric muscle action](image)

Fig. 6 shows the force-velocity relationship for a muscle contracting eccentrically (left half of figure) in comparison to a muscle contracting concentrically (right half of figure). The x-axis represents the shortening velocity of the muscle, while the y-axis (in the middle of the figure) represents the force developed by the muscle (Source: Huijbregts en J.P. Clarijs, 1999).

b) Eccentric muscle action:

The force-velocity relationship in an eccentric muscle action is opposite to that seen in concentric muscle action. When a load greater than the maximum isometric strength value is applied to a muscle fibre, it will begin to lengthen (eccentric contraction). At the initial stages of lengthening when the load is slightly greater than the isometric maximum, the speed of lengthening and the length changes in the sarcomeres are small. If a load is as high as 50% or more than the isometric maximum, the muscle will elongate at a higher velocity. The tension increases with the speed of lengthening in the eccentric muscle action because the muscle is stretching as it is contracting.

The force-velocity curve will end abruptly at some lengthening velocity when the muscle can no longer control the movement of the load. This relationship is shown in the left half of Fig. 6.
Moment of Inertia

According to Newton’s first law of motion, inertia is an object’s tendency to resist a change in velocity. The measure of an object’s inertia is its mass. The moment of inertia is a quantity that indicates the resistance of an object to a change in angular motion and is always measured relative to a point of rotation. The quantity of the moment of inertia generally depends on the object’s mass and shape (Hamill et al., 1995). In an extended object (e.g. a leg) the parts that are situated further away from the axis of rotation (e.g. axis of the hip joint) contribute more to the moment of inertia than the parts closer to the axis, i.e. the joint. This means that for 2 objects with the same total mass, the object with more of the mass located further from the axis will have a greater moment of inertia (Fig. 7) (modtech@theory.uwinnipeg.ca).

Fig. 7 shows two joint axes (black spots) which have a connection to a body segment with equal masses (triangles). A) is an example of a system with a small moment of inertia as the majority of the mass is close to the joint; B) shows a joint with a large moment of inertia as the mass of the segment is distant from the joint axis. Moving the extremity in A) requires a much smaller joint torque than the extremity in B) due to the mass distribution.

Moment arm

A moment arm is defined as the perpendicular distance from the action line of the force of a muscle to the joint where it is active (Hamill et al., 1995). A biarticular muscle will primarily act on the joint where it has the largest moment arm, or where it is further away from the joint.

For example, the HA muscles have a stronger moment at the hip, meaning that it will preferably act to perform hip extension rather than knee flexion. The RF muscle has a larger moment arm at the knee joint, therefore it is able to contribute more to knee extension than to hip flexion. Finally, the GA with a larger moment arm at the ankle than at the knee joint will add more to plantar flexion than to knee flexion.

The term ‘positive’ occurring throughout this paper in the context of joint moments stands for an extending moment while flexing joint moments are termed ‘negative’.

For the lower extremity hip extension, knee extension and plantar flexion are termed positive, while for the upper extremity shoulder extension and elbow extension are defined as positive. Further definitions of joint moments are not relevant in order to understand the contents of this paper.
Parallel cross-sectional area

The term PCSA is a measure of the number of sarcomeres in parallel. It determines a muscle’s maximum force-generating capacity (Murray et al., 2000). In other words, the larger the muscle volume the greater is the amount of force that this muscle can develop.

Coordination

Van Ingen Schenau (1988) defines “coordination” as the concerted action of muscles when performing a certain movement. As such, it is ultimately determined by timing, sequencing and amplitude of muscle activation.

Efficiency

This term is defined as the ratio of useful work output (e.g. work of the locomotor system) over the work input, such as the metabolic cost (Foss, M.L., Keteyian, S.J., Fox's Physiological Basis for Exercise and Sport, WCB McGraw-Hill, 1999). Thus efficiency relates external performance to the cost of that performance and is an important factor of locomotion. Efficiency is a parameter of energy flow through a system (muscle) that converts energy into another form. During the conversion, energy will be lost as heat which is not useful mechanically.

1.2 ARCHITECTURAL FEATURES OF BIARTICULAR MUSCLES

Definitions

Biarticular muscles are muscles which can produce moments at two adjacent joints simultaneously (Prilutsky et al., 1998). The definition that biarticular muscles span two joints is not always correct and can easily be misunderstood (Rozendaal, 1994). In the following, we will make the reader aware of some classification problems concerning mono- and biarticular muscles for both the lower and the upper extremity.

Lower extremity

The SOL muscle crosses two joints, one proximal and the other distal of the talus. However, as no muscles attach to the talus itself, this bone cannot be positioned independently from the position of the bones of the leg and foot. Therefore the SOL is excluded from the class of biarticular muscles. As it can only produce a moment at one joint it is classified as a monoarticular muscle. (Rozendaal, 1994)

Upper extremity

From a morphological point of view, muscles originating from the trunk and inserting in the arm pass the sternoclavicular, the acromioclavicular and glenohumeral joints.
In that case, muscles such as the pectoralis major, should be classified as biarticular. However, from a more functional point of view, they pass the shoulder girdle and the shoulder joint. The shoulder girdle moves with respect to the trunk synchronically in the sternoclavicular joint and the scapulothoracic gliding plane. Consequently, the muscles between trunk and shoulder girdle and those between shoulder girdle and arm are monoarticular (Rozendaal, 1994). In this paper we will also regard the PEC as a monoarticular muscle, for the same reason as explained above, namely that from a functional viewpoint it only exerts a moment at one joint, i.e. the glenohumeral joint.

Architectural features:

Two-joint limb muscles are often quite long and must withstand large length changes; their parallel fascicles often contain multiple, relatively short fibres. This large muscle length, compared to monoarticular muscles, can be achieved in two different ways:

1) Distal muscles often achieve their spans via long tendons which are attached to relatively short muscle bellies. Their fibre architecture is often highly pennate (feathered, winged), presumably to compensate for relatively small moment arms provided by tendons that pass close to the centres of rotation of the joints. The muscle mass is located proximally to minimize inertial mass in the distal portion of the limb, which often must be translated rapidly through space, e.g. during locomotion or jump.

2) On the contrary, proximal limb muscles are mostly designed quite differently in order to maximize torque and power output. Their attachments are often far away from the centre of rotation of the joints that they cross, giving these muscles large moment arms and joint moments. This results in proportionately large length changes during muscle contraction. In order to prevent over-stretching of their muscle fibres, these muscles must be nonpennate, with parallel muscle fascicles which run from origin to insertion, often containing relatively little tendon or aponeurotic sheet (Loeb et al., 1994).

1.3 THE CONSTRAINTS OF VAN INGEN SCHENAU

Translations of the body’s centre of gravity are predominantly a result of the transformation of rotations in joints into these translations. We will now look at the body in a mechanical way and describe the movements in the body as translations and rotations with help of the knee joint as an example. During knee extension a rotation occurs in the knee joint, i.e. the tibia rotates around the femur. This rotation in the knee becomes visible as a movement of the tibia through space, from a more flexed to a more extended position (Fig 8). This change of position of the tibia is termed translation.
Fig. 8. Model of a knee joint (KJ) with the segments thigh and shank; a) shows the starting position, with the knee joint in a flexed position. Between a) and b) one can imagine a rotational movement in the knee joint, indicated by the red arrow. The forward-downward translation of the tibia, which results in knee extension, is indicated by the green arrow.

The relationship between the rotation of a joint and the translation of a body segment can be seen in the following way: whenever a rotation in a joint occurs, the centre of mass (GCM) changes its position in space.

Let us look at the example of a patient getting up from a squatted position. We want to analyze the movements in the joints and describe them in terms of rotations and translations. This is shown below in Fig. 9. The starting position is a squatted position, i.e. all the joints (hip, knee and ankle) are flexed. Subsequently the patient extends his joints. The extending movements are rotations of the body parts (straight arrows). The vertical translation of the GCM is a result of these rotations.

Fig 9 shows the connection between the rotations (thick arrows) of hip, knee and ankle joints and the translations (thin arrow) of the GCM when moving from a squatted to a standing position.

Van Ingen Schenau (1989) describes four constraints which are associated with the transformation of rotations into the desired translations of the GCM or the centre of mass of a body part (PCM), such as the hand, foot or an object.
Geometrical constraint

During speed skating van Ingen Schenau (1989) measures the lever arm of the GA muscle. At the end of the push-off the knee extends while the ankle plantar flexes. It is stated that the translation of the GCM decreases with increasing knee extension, eventually reaching 0 at full knee extension. In other words, the transfer of the angular velocity to the desired translational velocity is less effective the more the knee is extended. This transfer of function is based on simple geometrical laws and is therefore defined as a geometrical constraint (van Ingen Schenau, 1989; Bobbert et al., 1988).

This constraint has been recognized as being universal (van Ingen Schenau, 1989), meaning that it is present in any (human or animal) movement where a translation is to be achieved by means of rotations in joints. So generally: the more the joint is extended the less effective the translational velocity.

What does this mean for practice? In a vertical jump this would mean that the transfer of angular velocity to the desired translational velocity is less effective the more the knee is extended. In other words the more the knee is already extended the less height is gained during further extension. This is shown in Figure 10.

![Fig. 10](image_url)

Fig. 10 the knee joint in two stages of extension: The vertical arrows indicate the gained height during knee extension. It becomes clear that less height is gained in the later stage of extension.

When we look at a jump we would now expect that the vertical translation decreases close to full knee extension, but this is not the case. Why? One answer to this question lies in the biarticularity of the GA. It can couple knee extension with ankle plantar flexion. While the knee extends, the ankle plantar flexes. Our body is a very intelligent machine because it does not extend all its joints at the same time, in fact the ankle plantar flexes after the knee extends and the knee extends after the hip extends. This is beneficial for the movement. We will explain in Chapter two why this is beneficial, for now it is enough to be aware that it is like this. As the GA is a knee extensor and a plantar flexor it couples these moments. It acts like a rope; the more the knee is brought into extension the more the ankle more the ankle is brought into plantarflexion. This is illustrated in Fig. 11.
Fig. 11 shows the coupling of moments by the GA during jumping. While the VAS and RF (not in the picture) extend the knee joint (KJ), the GA couples this extending moment to the plantarflexion moment at the ankle joint (AJ).

Relevance for physiotherapy

We could use this knowledge for strength training when we do exercises with our patients. When we keep in mind that our patient needs more force at joint angles close to full extension we could do very extensive strength training at these angles. Also resisted isometric movements would be more beneficial for strength training close to full extension. For assessment it is also wise to keep this in mind when we want to do a muscle strength assessment. When re-assessing a patient on muscle strength it is necessary to position the joint at the same angle every time, otherwise it may draw wrong conclusions.

Anatomical constraint

Van Ingen Schenau also discovered that we have to slow down the speed of the movements before reaching full extension.

If a movement takes place at a very high velocity it may force the joint into hyperextension causing damage to joint structures. In order to prevent damage being caused to body structures angular velocities are automatically decelerated to 0 prior to full joint extension (van Ingen Schenau, 1989). The deceleration is not achieved e.g. by the tightening of passive structures, but is instead an active process requiring antagonistic activity.

As an example, the HA muscles decelerate knee extension before the end position is reached. The fact that we have two-joint muscles is very beneficial in this situation. Imagine that the above constraints have to be overcome by means of monoarticular muscles only. The knee extension velocity would have to be decelerated to zero long before full extension is reached which requires deactivation of the knee extensors and eccentric contraction of a monoarticular knee flexor. Rotational energy would be lost as heat and the knee extensors would only be able to contribute to the effective energy over a limited shortening range. The two-joint muscles HA and GA slow down knee extension, minimizing joint damage.
Relevance for physiotherapy:

Imagine a patient with arthritis or joint damage of the knee joint. One possibility for rehabilitation is to strengthen the HA and GAS muscles in order to minimize further knee joint damage.

A patient with a rupture of the SM muscle will need to increase the strength of the remaining hamstrings muscles in order to assure that the knee joint is efficiently protected from damage during explosive knee extension.

Van Ingen Schenau stated two more constraints which are also important in order to understand coordination and are based on simple mechanical and geometrical features. They are rather descriptive in nature.

The first one deals with the required distribution of net moments in the joints when exerting an external force in a desired direction. In order to move in different directions, i.e. to exert an external force towards the ground in different directions, different net moments in the joints are required in order to produce the desired outcome. This is obvious when one compares a jump that is forward directed with one that is backward directed. For further information see also Jones et al. (2003) who investigated in this field and also found different patterns for different jumping directions.

The last constraint described by van Ingen Schenau (1989) deals with the desired average direction of the external force, e.g. on the hand or foot, during a proximal-distal sequence of the onset of joint rotations which are necessary to solve the problems associated with the geometrical constraint. In other words, the external force, e.g. in the direction of a jump, determines the sequence in which the segments are accelerated and in which sequence the energy is transferred between the segments. The proximal-distal sequence stays more or less the same, regardless of the direction of the jump, yet the intensity of the rotations may differ depending on the desired direction. Jones et al. (2003) studied different jumping directions with respect to the moments, muscle activations and segmental displacements. It was found that different jumping directions require a different sequence of muscle activation and, because of this, a different distribution of net moments.
Chapter II

The functions of biarticular muscles
This chapter introduces two major functions of biarticular muscles: the proximo-distal sequence and the energy transfer amongst segments. Both topics are closely related and have therefore been combined to form one chapter.

The transfer of energy

Biarticular muscles are said to have the function of transferring energy among joints. The energy which is transported is to a great degree not developed by the biarticular muscle itself but by strong monoarticular muscles. This ability of a muscle to cause an exchange of energy among segments can be more important for the execution of a task than its ability to produce energy and deliver it to the segments which it crosses (Zajac, 2002).

The direction of the energy transfer can be either in a distal-proximal direction or in proximo-distal direction. In this chapter we will concentrate on the latter.

This idea of proximally located muscles being able to transfer power in order to support movements of more distally located joints goes back to Elftman (1939) and has recently been confirmed by many authors such as Bobbert et al. (1988); van Ingen Schenau, (1989), van Ingen Schenau (1990); van Ingen Schenau et al. (1992); Jacobs et al. (1996); Prilutsky et al. (1994); de Lussanet et al. (1997); Raasch et al. (1997); Novacheck (1998).

What are the advantages of this mechanism?

One major advantage of the ability of biarticular muscles to transfer energy distally is that it enables distally located muscles to be smaller in size than the ones located more proximally. In this way, relative low moments of inertia occur at the joints (van Ingen Schenau, 1990). In a more recent study, Prilutsky et al. (1994), conclude that one-joint muscles of the proximal joints compensate for the deficiency in work production of the distal one-joint muscles which results from smaller muscle-belly sizes. This ‘compensation’ is especially necessary in ballistic movements, such as the jump, during which high acceleration velocities are required to propel the body upwards. A concentration of large muscle bellies at distally located body segments (e.g. at the shank) would lead to an increased moment of inertia. Consequently, in order to achieve high acceleration velocities, as they are required for the performance of a ballistic movement (e.g. the jump), a much higher energy production would be necessary in order to achieve the same result (e.g. jumping height) as a system with a small moment of inertia.

For the transfer of energy to take place a co-activation of monoarticular agonists and biarticular antagonists is required. This means that the energy produced by large monoarticular muscles spanning the proximal joints is efficiently transferred to distal joints by the action of biarticular muscles (Jacobs et al., 1996). By means of a tendinous, “rope-like” action the biarticular muscle can transfer the mechanical output of concentrically contracting monoarticular muscles to those joints where it can be used most effectively (van Ingen Schenau, 1992). The ‘rope-like’ function should be understood as an (almost) isometric contraction of the biarticular muscles during certain movements. When pulling at a two-joint muscle at one end, i.e. at one of the joints it crosses, it needs to give way at the
other joint; otherwise it would have to increase its length and would no longer be able to contract isometrically.

As an example, during jumping, the hip and knee joints both move from a flexed to an extended position (Fig. 8a). For the RF this means it is pulled at from its proximal end due to hip extension. But as it is contracting isometrically, i.e. not changing its muscle length, it has to ‘let loose’ at the knee joint; this is achieved by allowing knee extension.

Van Ingen Schenau (1990) shows that in jumping the RF transfers power which is produced by the GU muscle from the hip to the knee joint. In order to prevent a further ‘useless’ acceleration of the knee angular velocity towards the end of knee extension, the GA transfers power from the knee to the ankle joint, contributing to the total amount of work in plantar flexion. So in fact, not only the VAS but also the GU muscle contributes to plantar flexion in the final phase of the push-off in jumping due to the capability of the RF and GA muscles to transport energy from proximal to distal segments.

Van Ingen Schenau (1990) also claims that the biarticular parts of the HA muscles transfer energy during jumping. As RF and HA muscles are active simultaneously throughout the jump, one speaks of a co-activation of these muscles. This may sound paradoxical, but in fact, this co-activation results in hip and knee extension due to differences in moment arms between these muscles at the hip and knee joint. While the HA have the larger moment arm at the hip joint, the RF muscle has the larger moment arm at the knee. One could now assume that, as both muscles have the ability to transfer energy, power will ‘run around’ between the hip and knee joints. Due to the differences in moment arms, however, the power liberated in the HA muscles appear as an increase in power in the knee joint as long as the force in the RF is larger than that of the HA (van Ingen Schenau, 1989). In this case, the HA may have two functions: (1) they ‘act’ like a monoarticular muscle by supporting the GU muscle to extend the hip joint. And (2) the HA may also dissipate energy from the knee joint, especially toward the end of maximal extension. By decelerating knee extension, the HA muscles can be useful to prevent the knee from hyperextending (see also the chapter on the ‘anatomical constraint’). Fig. 12 shows the segmental movements during jumping and indicates the direction of the energy transfer (black arrows) amongst the biarticular RF, RF and GA muscles.

The study of Jacobs et al. (1996) shows that the relative work contribution of the HA muscles to hip extension in jumping is 7 %. For the RF, the relative work contribution in knee extension is 21%. It is also said that 25% of the total amount of work done at the ankle in jumping is due to a transfer action by the GA from the knee to the ankle joint. These findings support the hypothesis that the action of biarticular muscles contribute to a net transfer of power from proximal to distal during explosive leg extensions, such as the jump.
Fig. 12a and b illustrate the segmental movements during jumping and the energy transfer. The thick red arrows indicate the action lines of the muscular force; the thin black arrows indicate the direction of the energy transfer.

Energy transfer in other movements:

Aside from vertical jumping, as is shown above, the mechanism of energy transfer is also important for other dynamic and also static tasks. Van Ingen Schenau (1992) concludes that a transfer of energy between the HA and RF during static leg tasks takes place.

Energy transfer is also shown to occur during dynamic tasks such as cycling (van Ingen Schenau, 1992; Fregly et al., 1996; Raasch et al., 1997), walking (Prilutsky et al., 1994) and running (Novacheck, 1998).

Also for explosive leg extensions as they occur in sprinting, jumping and skating, an energy transfer from proximal to distal takes place (Bobbert et al., 1988; van Ingen Schenau, 1989; Jacobs et al., 1992; Jacobs et al., 1996).

Proximo-distal sequence

The proximo-distal sequence, which this part of the chapter emphasises on, is in fact a form of energy transfer.

While the first part of this chapter gives a general overview of the transfer of energy and how it plays a role in movements this part shall give the reader more insight into the mechanisms which take place.

In the following, we will use the example of the squat jump in order to explain these mechanisms.

In the starting position the trunk, as well as the hip, knee and ankle joints are flexed. The aim of the jump is, from a kinesiological point of view, to translate the GCM of the body vertically as much as possible. In the starting position the GCM is rather close to the floor and throughout the movement it will be translated vertically. To achieve this, the segments have to be extended and the body has to produce force in order to attain both the
extension of the segments and the propulsive force that causes the body to leave the ground, translating the GCM upward as far as possible. Bobbert et al. (1988) investigated the sequence of segmental acceleration, meaning the order in which the segments of a jumper are extended. They found that the upper body is extended first, followed by the upper leg, the lower leg and finally the ankle. This is illustrated in Fig. 13. Besides that, Bobbert et al. (1988) hypothesized that those biarticular muscles (RF, HA and GA) which are active throughout jumping transfer the energy produced by the monoarticular muscles to more distally situated joints. This will be explained in more detail in chapter 5.

Fig. 13 shows the proximo-distal sequence in four phases. The arrows represent the direction of the rotation of the segments.

The question which arises is: What is the benefit of this subsequent acceleration of the body parts?

This is explained by Bobbert et al. (1988) in their kinematical analysis of the velocity differences between the segments. They state that in order to obtain a maximal vertical translation of the GCM the vertical velocity differences between the ends of the segments should attain their peaks in a sequence from proximal to distal.

Bobbert et al. (1988) state that when a proximal segment is extended it exerts a downward directed force onto the more distal segment, via the joint that connects them both. If both segments were extended simultaneously the muscles acting on the lower segment would have to overcome the downward directed force when extending the lower segment. This would cause an unnecessary loss of energy. This is one reason, but not a complete explanation for this sequence.

The second part of the explanation concerns the biarticular muscles. Bobbert et al. (1988) investigate their activation pattern with the help of surface EMG. The EMG levels of different muscles reach their peak in the following sequence: ST, BF caput longum, GU, VM, RF, SOL and GAS. The first muscles that reach their peaks are the HA. They deliver energy to the trunk during extension. Their function as knee flexors can be neglected as they hardly contribute to any additional knee flexion during the first phase of the push-off. To understand this, one has to be aware that the HA acts rope like in this situation. They have a flexing moment at the knee joint but the extending moment of the RF and the VAS is bigger. The HA therefore transfer energy from the knee joint to the hip joint, coupling the knee extension with hip extension.

The biarticularity of the RF as well as of the GA is beneficial if we consider the anatomical constraint introduced by van Ingen Schenau (1989). At the termination of the
movement, which is shortly before a joint reaches full extension, it has to be decelerated in order to avoid damage to the joint and joint structures. If the body consisted only of monoarticular muscles the monoarticular extensors would have to be deactivated before the termination, which would be counter-productive. The flexors would have to work eccentrically, and therefore the excessive energy would be converted into heat. The biarticularity of the RF and GA offers an elegant solution for this problem. Activation of the RF helps to reduce the net moment at the hip and therewith the rate at which the angular velocity of the upper body increases. As soon as knee extension commences, the RF transports energy from the hip to the knee. Of course, this is very practical as the transported energy can now be used at the knee joint. A similar action is performed by the GA. This muscle can transport the energy which is released by the knee extensors to the ankle.

These findings suggest that biarticular muscles play an important role during explosive leg extensions as they are capable of transferring energy and, with that, save energy compared to a system consisting of monoarticular muscles only.

In short, we can speak of three ropes (RF, HA and GA) which couple the moments between the hip, knee and ankle joints by transferring energy between them (Fig. 14.).

Fig. 14 shows how the three biarticular muscles RF, HA and GA couple the segmental movements and act as ropes to transfer the energy distally and, in case of the HA, proximally.

To conclude, the term 'proximo-distal sequence', which is directly connected with the energy transfer between segments, consists of the analysis of the segmental movements, the muscular action as well as the interpretation of the two.

The following shows some further research which also confirm the occurrence of the proximo-distal sequence.

Jones et al. (2003) investigate the role of one- and two-joint muscles in countermovement, i.e. squat jumps, in different directions. Although they do not investigate the segmental patterns their figures support the hypothesis of Bobbert et al. (1988). They indicate that there is an ordered sequence in the segmental movements starting with the most proximal segment; this sequence is the same for all jumping directions.

Van Ingen Schenau (1989) suggests that a system consisting only of monoarticular muscles would lead to much higher energy requirements, especially during ballistic tasks, as they require a large amount of eccentric muscle activity which leads to heat
production and therefore energy loss. Besides that, the distally located muscles would need to produce a lot more power than in a system containing both mono- and biarticular muscles as no energy is transferred from proximal to distal.

Herzog et al. (1994) analytically investigate the effects of replacing two-joint muscles with energetically equivalent one-joint muscles on cost effectiveness.

However, during such movements the biarticular muscles are shortening at both joints, and thus, the shortening velocity of these muscles is higher than for corresponding monoarticular muscles. Therefore, the ability of biarticular muscles to generate maximal forces is lower than for the corresponding monoarticular muscles.

One may conclude that the major function of biarticular muscles is not associated with providing moments in the muscle’s direction, simultaneously at two joints.

The researchers admit that, as the analysis is performed exclusively for static conditions, further research is necessary before conclusions can be drawn for dynamic movements.

Other opinions:

In their optimal control model of jumping, Pandy et al. (1991) replace the GA with a monoarticular plantar flexor. As this adjustment leads to only a minor difference in jumping performance, Pandy et al. (1991) conclude that the action of GA does not differ from that of any other monoarticular plantar flexor. However, it has been argued that the moment arm of the GA in the knee joint is unrealistically small (van Leeuwen et al., 1992) and no anatomical constraint has been included in the study. Therefore, we do not consider the results of the study of Pandy et al. (1991) as being decisive.

Relevance for physiotherapy

Having knowledge about the proximo-distal sequence and the mechanism of energy transfer during specific movements can be of great practical value for a physiotherapist. The main purpose of this chapter is to demonstrate that a multi-joint task (i.e. a task involving movements in more than one joint) should be seen as a sequence of actions which are closely connected and should not be regarded as isolated muscle contractions and joint rotations.

As a consequence, a (biarticular or monoarticular) muscle injury will most likely not only effect the joint(s) which it crosses but, due to the transfer of energy and the co-activation of mono- and biarticular muscles, we hypothesize that, it may also affect other more distally located body segments. An injury of the monoarticular GU, for example, may lead to a reduction in energy production; therefore less energy could be transferred by the biarticular antagonist, the RF. This energy shortage would also affect the more distally located segments, so that the GA would also transport less energy than usual. The end result, meaning the jumping performance, would be reduced.

When aiming at improving jumping e.g. performance the physiotherapist must keep in mind that several segments are correlated and that a) muscle or joint damage can strongly affect sequences of various movements and b) decreased (jumping) performance can have many different causes and it is up to the physiotherapist to find and ‘repair’ the weakest link in the chain.
To conclude, it has been shown that the transfer of energy, and with it the proximo-distal sequence, among segments achieved by biarticular muscles plays a major role in the performance of static leg tasks, as well as in both ballistic and non-ballistic dynamic tasks such as cycling, walking, jumping, skating and running. These are just a few examples but most likely, the phenomenon of energy transfer also counts for many other movements which have, to date, not been investigated on or which have not been mentioned in the present paper.

We claim that this knowledge is of major importance for physiotherapists and should always be kept in mind throughout treatment.

2.2 ACCELERATION AND DECELERATION

Acceleration and deceleration are terms derived from mechanics. They are used to illustrate the interaction between the body segments and the muscles to describe the influence that muscles have on the body segments. This knowledge can be used to analyze movements in the body and describe the action of muscles in a specific movement. It may also help us to understand the role of a muscle during a certain movement and to understand why muscles contract isometrically, concentrically or eccentrically.

Two-joint muscles have a special function as they are able to combine acceleration of one segment with deceleration of another segment - a fact which is very beneficial for human movement. For the physiotherapist it is important to know this in order to understand the complications a patient might face in executing movements after a muscle injury or pathology of the musculoskeletal system.

We will explain the concepts by means of a common athletic activity, the squat jump. Finally, we will use two examples to demonstrate how this knowledge can be put into practice by physiotherapists.

As previously described, a muscle can redistribute mechanical energy among the body segments during task execution. Each muscle causes reaction forces throughout the body with the net effect that some segments are accelerated and some are decelerated (Zajac, 2002). Place an object on your table and give it a push. In order to move it away from yourself you first have to overcome the mass of this object. This means you need to push hard enough in order to move the object. The same accounts for a muscle that needs to move a bone. This muscle has to first overcome the resistance of the bone. This resistance can be described as the reaction force. Recall at this point that movement of segments ought to be seen as rotations at joints around axes which lead to a displacement (translation) of the GCM (Fig. 9). At this point we will combine this knowledge with the theory of the chapter about rotations and translations.

Acceleration of a segment is necessary in order to cause a translation, while deceleration of the segment is required to prevent the occurrence of joint damage. These segments are connected by muscles and these muscles cause the rotations at a joint through their moment. Take the simple task of flexing the elbow. The elbow flexors contract and by this cause a rotation at the elbow joint which leads to a displacement of the segment, in this case the forearm. The forearm in this example is accelerated in relation to, for example, the upper arm which remains still. This is shown in Figure 15.
Fig. 15 shows isolated elbow flexion. The biceps brachii (BIB) accelerates the lower arm (LA) in relation to the upper arm (UA) causing a rotation of the segment of 90° flexion. S stands for shoulder, GH glenohumeral joint and E stands for elbow joint.

This was an example of a movement in which only one segment is accelerated and then decelerated at termination of the movement to prevent potential injury of the joint. Deceleration of body segments may be caused by various structures. The deceleration can be caused by various structures.

Two-joint muscles are able to accelerate one segment and at the same time decelerate another. Take as an example a person performing a squat jump. The GA is able to perform both knee flexion as well as plantar flexion of the ankle joint. When combining these two movements, the GA muscle decelerates knee extension prior to full extension and simultaneously accelerates the ankle into plantar flexion which is necessary to achieve propulsion. If, instead of the GA muscle, the human body were equipped with a monoarticular knee flexor this muscle would have to be eccentrically active throughout the movement; it would therefore be prone to injuries and also convert valuable energy into heat. This is illustrated in Figure 16. Energy which is converted into heat it is ‘lost’ for the specific task. The body wants to avoid this as it would require a higher energy uptake (so we would have to eat more).

Fig. 16a) shows a squat jump with a two-joint GA; Fig. 16b) shows a squat jump with SOL and a hypothetical monoarticular knee extensor. The red line at the knee joint in b) represents eccentric activity of the monoarticular knee flexor occurring during upward propulsion.
Multiple muscles working together with the aim of accelerating the same segments and decelerating others are termed “co-functional” (Zajac, 2002). Co-functional muscle activity may be required when segmental energetic exchanges are so high that one muscle cannot deliver sufficient energy on its own. Co-excited muscles can also work synergistically but not co-functionally, i.e. the segments accelerated by muscles causing oppositely directed segmental energy exchanges to occur (Zajac, 2002); one muscle produces the energy and another causes the opposing segmental accelerations and decelerations to enable the energy to reach the target segment. In the squat jump the GU would produce the energy that is transferred by the two joint muscles to the distal segments. This is shown in Fig. 17.

In Fig. 17a the GU contracts concentrically, extending the HAT segment. GU accelerates the HAT segment. The RF decelerates the HAT segment and accelerates the thigh into extension at the knee joint. The energy for this is derived from the GU. Fig 17b shows what happens between the thigh and the foot. The GA decelerates the thigh, preventing joint damage prior to full extension (anatomical constraint). At the same time it accelerates the foot into plantar flexion, so coupling knee extension with plantar flexion. The ankle plantar flexion can be decelerated by the TA. The straight arrows indicate the action line of the muscle force; the curved arrows indicate the direction of the segmental rotations.

We can derive some basic principles in order to explain the concept of accelerating decelerating more clearly: Segmental energy increases in the accelerated segments and decreases in the decelerated segments.

If a muscle contracts isometrically the generated force can still cause an energy increase in some segments and a decrease in others by distributing the force from one segment to another. When one muscle accelerates a segment another muscle may be activated which decelerates the segment accelerated by the first muscle and therefore accelerates the target segment that cannot be reached by the first muscle. The second muscle acts as a transmitter of the force produced by the first muscle this is called a muscle synergy for a specific movement and this has to be analyzed to understand more complex movements than the one in the first example. In our example the GU would be co-functional with the RF as, through the energy transfer by the RF muscle, the GU accelerates the thigh and shank into extension. While GU produces the force the RF acts as a transmitter; both muscles therefore act as synergists.

Zajac (2002) studies the human squat jump with the help of an inverse dynamical analysis. His findings are listed and discussed in the following:
The monoarticular hip extensors develop most of the propulsive energy, with the proximal extensors excited first.

The biarticular leg muscles redistribute the segmental energy without producing much energy themselves, except for the GA.

The reason why the GA produces energy is probably to achieve a higher jumping height. But by nature this indicates that the GA indeed slows down knee extension, in synergy with the hamstrings, because when they are active they both have a flexing moment at the knee joint, opposite to the extending movement.

RF is an energy sink, meaning it was eccentrically active. The RF therefore does not transfer all the energy created by the hip extensors to the knee joint but dissipates some of it. This is may be explained by an excessive energy generation at the hip joint. The reason why not all the energy produced is transferred might be to prevent the knee joint from being damaged.

**Relevance for physiotherapy**

**Examples:**

a) A 25 year old professional volleyball player with a femur fracture; besides atrophies of the RF and HA muscles he has recovered well. His rehabilitation training includes jump training and running five times per week. After one week he starts complaining about knee pain, which seems to be located in the joint. Further he complains of pain in his HA and RF and he frequently reports muscle cramps especially in the HA. Possible explanations: The reason for his pain in his knee joint may be due to the fact that the RF and the HA are not able to protect the knee joint from damages because they are still too weak to decelerate the segments sufficiently. The volleyball player should start with a strengthening program for his HA and RF muscles before returning to his previous exercise program.

b) Another patient is a football player, complaining of pain in both his knee joints. It seems to be the same pain as was reported by the volleyball player in the example above. The pain is more pronounced in the left knee joint but is also occurring in the right knee joint since one week. During patient history one discovers that he started practicing yoga a few weeks ago. A major part of these yoga sessions is to do stretching exercises, especially of the leg muscles. It is suspected that the patient ‘over-stretched’ his HA muscles.

As a consequence they may not able to decelerate the shank sufficiently in order to prevent force full knee extension; this provokes pain and on the long run may cause damage to the knee joint.

Appropriate advice for this patient would be to stop stretching the HA muscles, while treatment should emphasize on coordination and strength training of the HA muscles in order to improve their function of preventing damage to the knee joint.
Many tasks involving more than one joint require that joint torque and change of joint angle have opposite sign (Gielen et al., 1998). In other words there is a discrepancy between the moment occurring at a joint and the actual movement taking place. The aim of this chapter is to present a further function of biarticular muscles, namely the capability to solve the problem of contradictions between moments and movements occurring at joints.

In general, the control of an external force always requires a particular distribution of net moments over the joints. Each combination of net moments will lead to a particular direction and magnitude of the external force at given inertial and gravitational forces. While monoarticular muscles are activated in order to deliver force when they can contribute to positive work, biarticular muscles are activated in order to achieve the distribution of net moments over the joints which is necessary to control the direction of the external force (van Ingen Schenau et al., 1992).

Most movement tasks require two types of transformations: one of position and one of force. The transformation of muscle displacements into joint rotations are transferred further into the required displacement of e.g. the hand or foot. The transformation of muscle forces into joint moments is transformed further into the direction and magnitude of the required external force (Fig.18).

The requirement for the control of an external force should be regarded as being essentially independent from the requirement for joint displacements in many tasks (van Ingen Schenau, 1990).

If only monoarticular muscles were active, irrespective of the type of movement, they would dissipate, rather than contribute to positive work. Consequently, other (monoarticular) muscles would have to produce more work in order to execute the task and to generate the work which is dissipated at other muscles.

Biarticular muscles solve this conflict as they do not make lengthening of the activated monoarticular muscles necessary and thereby contribute to a higher efficiency of the motor system in cases when monoarticular muscles would be lengthening while being activated (Gielen et al., 1998). Biarticular muscles can distribute joint forces so that monoarticular muscles can remain active; therefore no energy is lost through eccentric activity.
The following example shows a daily task in which the described conflict between moment and movement of a joint occurs and is successfully solved by biarticular muscles.

Imagine somebody sitting at a horizontal table who has to displace an object in the indicated direction (Fig. 19). In order to perform this displacement the person needs to perform an extension movement in the elbow joint while the counteraction of the reaction force requires a net flexing moment in the elbow and also in the shoulder joint. This means that the sign of the necessary net moment in the elbow (negative due to the flexing moment) is opposite to the sign of the required joint displacement (positive due to the extending movement).

Now imagine that the arm performing the displacement consists of monoarticular muscles only. The only possible way to perform this task would be that the shoulder flexors deliver considerably more work than the work done on the object while the difference is converted into heat in the eccentrically contracting elbow flexors. Activation of the elbow extensors would be useless as the flexors would have to reduce the net moment to the required net flexing moment. If elbow extension were to contribute to the external work on the object, the displacement would not be in the required direction as shown in Fig.??; instead it would be directed much more laterally.

Consequently, all work done by the concentrically contracting (monoarticular) elbow extensors would have to be converted into heat.

These conflicting requirements with respect to the net moment at the elbow would lead to a waste of energy and also to a situation where muscles which are in the position to shorten (in this case the elbow extensors) and to contribute to positive work, have to remain passive.

The solution: the biarticular BIB

The BIB is able to solve this conflict, as it fulfills both requirements of a flexing moment at the shoulder joint and of a flexing moment at the elbow joint. In order to displace the object the BIB needs to overcome two forces: (1) the reaction force of the object $F_{\text{ext}}$ and (2) the reaction force of the (upper) arm. This is achieved simply by contracting isometrically. When picturing the BIB as a rope we will notice that during shoulder flexion, the rope will become slightly ‘loose’ at its proximal end. In order to maintain its length it needs to ‘tighten’ at its distal end. This is achieved by means of slight elbow extension.

To conclude, the conflict moment-movement which occurs when performing the task of moving an object horizontally across a table in the direction as indicated in Fig. 19 can be solved by means of an isometric contraction of the BIB. As lengthening of activated monoarticular muscles is not necessary, the BIB contributes to muscle efficiency (Gielen et al., 1998).
Fig. 19 is a schematic drawing of a subject exerting a force against an external force $F_{\text{ext}}$ (brown cubes). The direction of the reaction force ($F_{\text{ext}}$) is indicated by the straight thin arrow. The thin red lines indicate the lever arms which the $F_{\text{ext}}$ exerts on the elbow and shoulder joints. Moving the object in the indicated direction (thick straight arrow) requires a flexion torque in elbow and shoulder joints (curved black arrows). The task, however, requires an extension of the elbow joint (curved red arrow) extension of the elbow, which means that the change in elbow joint angle (extension) and the moment occurring at the elbow joint (flexion) are opposite in sign.

One must keep in mind, that by changing the direction of the external force, e.g further laterally, the requirements concerning moment and movement will also change. A laterally directed force will require an extending moment at the shoulder joint and an extending moment at the elbow. In this case, the muscle activation pattern differs from the example above.

Relevance for other movements:

Other research studies show that the conflict as described above also occurs throughout other movements.

Van Ingen Schenau (1990) shows that a conflict occurs between the control of the direction of the force and the displacement of the foot during cycling. The problem is once again solved by a biarticular muscle, the RF.

Novacheck (1998) demonstrates how the HA muscles solve the conflict between the movement and the moment at hip and knee joints during gait. Due to limited space, we will not describe these mechanisms any further.

To conclude, the existence of biarticular muscles contributes to a higher efficiency of the motor system during multijoint movements. In comparison, a system consisting of only monoarticular muscles would lead to a considerable waste of energy as eccentric muscle activity would be necessary to solve the conflict of opposite moment – movement directions.
Relevance for physiotherapy

When training coordination with patients one should keep in mind that the direction of the external force may influence the muscle activity. Therefore, even the ‘simple’ task of pushing an object over a table will require the activation of different muscle (coordination) patterns, depending on the movement direction. On the one hand, this knowledge is advantageous as we can use it when training specific muscles directly. On the other hand, we should be aware of the fact that we may easily train the ‘wrong’ muscle group by making a slight change in the direction of the external force.

The finding of van Ingen Schenau (1990) that the requirement for the control of an external force should be regarded as being essentially independent from the requirement for joint displacements in many tasks is of great relevance for physiotherapists.

To date, research has only been able to analyse a few movements of the many possibilities. Therefore many questions remain unanswered concerning the moments and movements occurring at joints during various tasks.

The message behind this chapter is that the musculoskeletal system is much more complicated than it seems to be. A movement such as elbow extension, which is what we can observe, may not necessarily require an activation of the elbow extensors as shown in the example above. Physiotherapists should keep this in mind when performing strength training with their patients.

In the following, we will give an example taken from physiotherapeutic practice in which the contradiction moment – movement should be taken into consideration.

Fig. 20 shows a possibility of coordination training, e.g. in patients with neurological disorders, such as hemiplegia or cerebral palsy. The idea of this exercise is to place different shaped objects into their matching holes on a board. Note that every object requires a different combination of net joint moments and hence muscle activity.

Fig. 20 shows the task of placing a circular object into its matching hole (top left). 20a shows the action line of the force. The yellow arrow indicates the line of translation of the object through space. The black
arrow indicates the direction of the reaction force. The black vertical arrows indicate the lever arms of the forces that act on the elbow and the shoulder joint respectively, causing an extension moment at the elbow and a horizontal abduction moment at the shoulder. In order to reach the target hole the patient needs to produce a flexing movement at the elbow and an adducting movement at the shoulder. To achieve this he has to activate the elbow flexors and the shoulder adductors. The muscle best suited for this is the BIB.

Fig. 20b shows the end position of the movement. The elbow is extended although we saw in the last picture that a flexing moment is required to overcome the external force. This explains why the BIB is active in this example although extension is necessary. The reason why extension is happening is very simple: The patient needs elongation in order to overcome the distance in space. The force that causes the extension is the external force.

### 2.4 Direction of an External Force

**Introduction:** An external force is a force applied from the world on to the body. An external force can be, for example, the ground reaction force (GRF). It can also be the resistance of an object which is to be moved. To elaborate this we want to look at a person performing several jumps. It has been shown for the upper extremity that differently directed external forces require different activation patterns in the corresponding limb (van Bolhuis 1998). The same counts for the lower limb. There are studies that support this hypothesis (Jones et al. 2003), also studies that investigated on the role of the mono- and biarticular muscles.

This chapter is concerned with the question if there is a difference between the activation patterns of mono- and biarticular muscles and if yes could external forces be the underlying cause for this? Can we establish an advantage of the biarticular muscles when we investigate on the activation patterns?

It is suspected that monoarticular muscles play a different role, meaning they have a different task, than biarticular muscles. In multisegment movements, the contributions of monoarticular muscles may differ from those of biarticular muscles (van Ingen Schenau, 1989). They play a role in tuning joint moments so that the external force can be applied in a specific direction. A popular hypothesis is that monoarticular muscles deliver the force needed for a movement and the biarticular muscles would be responsible for transmitting the force between the joints and in the end, in the case of a jump, to the ground. (Jones et al. 2003; Kumamoto et al., 1994; Neptune et al., 1998; Savelberg et al., 2003; van Ingen Schenau et al., 1992; 1995).

Why do we need to transmit force to the ground? In order to perform a jump a force needs to be exerted onto the ground so that we can push ourselves away from the ground, i.e. to overcome gravity for an instant. If we want to jump forward we have to push ourselves forward and upward, if we want to jump backwards we have to push ourselves backwards and upwards. One of Newton’s laws says that action equals reaction. In other words, when we exert a force onto the ground the ground reacts with another force that according to Newton is equal in magnitude but opposite in direction. This is the ground reaction force. This force can be measured with a force plate; this is sometimes done by physiotherapists. In figure 21 the force exerted on the ground and the ground reaction force are illustrated while a subject pushes him-/herself off the ground in two different directions. It is hypothesised that it is the function of biarticular muscles to direct this force (Jones et al. 2003; Bobbert & van Ingen Schenau, 1988).
Fig. 21: Fig. 21a shows a subject’s ankle and shank. The situation shows a subject just prior to push-off. The external force is represented as the normal force ($F_N$), the vertical vector and the parallel or friction force ($F_P$), the horizontal vector. The subject is going to perform a forward directed jump. Fig. 21b shows the same subject performing a backward directed jump. The direction of $F_P$ has changed. This is required for the push-off in a backward directed direction. According to the hypothesis that monoarticular muscles produce the force and biarticular muscles direct the external force this would mean that the biarticular muscles have a different activation pattern in a than in b. The picture illustrates that the difference between a backward and a forward jump is in the direction of the horizontal force vector, whereas the vertical vector stays the same.

Jones et al. (2003) show that for jumping in different directions the biarticular muscles are activated differently. This means that there is a connection between the direction of the force and the activation of two-joint muscles. When first jumping forward and then backward ones muscles will be activated differently. For a backward directed jump we need to push ourselves off the ground in a specific direction. The force we exert on the ground has a forward direction. In order to exert this force a flexing moment at the hip and an extending moment at the knee joint is required. For this the RF would be suited perfectly. When performing a forward directed jump the force applied to the ground needs to be in a backward direction (we push ourselves off the ground) this requires a backward directed force which is achieved by exerting an extending moment at the hip and a flexing moment at the knee joint. The HA are most suited for this combination of joint moments.
A forward-directed external force, red arrows, (Fig 10a) requires both hip flexor and knee extensor moments, a combination suited perfectly for the RF. Likewise the HA muscles could contribute to both hip extensor and knee flexor moments which are necessary for a force vector applied in the posterior direction (Fig 10b) (Jones et al, 2003). The green arrows indicate the moment of the force on the joints. These moments have to be overcome by the muscles in order to jump and to overcome gravity.

As muscles are the ones that produce movements on the joints, where, depending on forces required, exert more or less force. The force required for the movement depends on, amongst others the external force. One could assume that there is a connection between the required movements and the muscles that are active. If this is so it should be possible to measure differences in muscle activity when one changes the jumping direction. The biarticular muscles may play a role in regulating the direction of the external force. They might have an advantage compared to the monoarticular muscles as they can couple two moments and therefore affect two joints at the same time.

Jones et al. (2003) carried out a study on muscle activity during jumping in different directions. Their hypothesis is that there may be different activation patterns for mono- and for biarticular muscles. It is suspected that monoarticular muscles would demonstrate the same activity regardless of jump direction, based on pervious studies which suggest their role is to generate energy to maximize GCM velocity. In contrast biarticular muscle activity is expected to change in order to control the direction of the GRF and the translation of the GCM. In other words: monoarticular muscle activity would not be influenced by the direction of a jump whereas biarticular muscle activity would be. Fig. 23 indicates the relationship between the jumping direction and the direction of the GRF.
Jones et al. (2003) measure the kinetics, kinematics and muscle EMGs of several leg muscles in four different jumping directions. They are termed backward (BJ), vertical (VJ), intermediate (IJ) and forward jumping (FJ), with intermediate being between vertical and forward. The jumps include a countermovement phase; the subjects assume a squatted position as the starting position for the jump. The position of the squat alters between the different jumping directions.

It is found that the activity of the biarticular leg muscles, HA, RF and GA, varies statistically significant with jumping direction; the largest variation in muscle activity is shown by the HA.

Muscle activity decreases in the following order:

HA:  \[ \text{FJ} \rightarrow \text{IJ} \rightarrow \text{VJ} \rightarrow \text{BJ} \]
RF:  \[ \text{IJ}, \text{VJ}, \text{BJ} \rightarrow \text{FJ} \]
GA:  \[ \text{FJ} \rightarrow \text{IJ} \rightarrow \text{VJ} \rightarrow \text{BJ} \]

These findings show that the activation of the two-joint muscles listed above varies with the required jumping direction. Biarticular HA and RF activity differences may be related to the need to arrest and reverse varying amounts of HAT (head, arm and trunk segment) forward flexion (Jones et al., 2003). HA activity seems to increase when HAT flexion increases and vice versa. FJ has highest HAT flexion, BJ the lowest.

For the monoarticular muscles, GM, VL and SO, a similar peak activity is found for all jumping directions; only in late propulsion GM and VL activity depended on jump direction.

To summarize, we can state that activity patterns of the measured one- and two-joint muscles fit to the hypothesized roles given to them by Jones et al. (2003).

The one-joint muscles usage was similar in all jump directions because of the common need to generate energy during lower extremity extension. This hypothesis was supported by the lack of statistical differences in peak patterns, but not by the average EMG data or qualitative analysis of activity patterns. This means that for example VL activation reached the same peak in all four jump directions, but the average level of activity and activation time varied with different jumping directions. Also the GM and TA activity varied in different jump directions, not the peak, but the average activity.
Biarticular muscle activity patterns vary with jump directions. One possible explanation for this could be the following: There might be a conflict between the task of energy transfer across joints and the GRF direction control. Conflicts between energy transfer and GRF directional control were avoided by initiating and developing the appropriate jump direction during the countermovement.

Differences in the activation of mono- and biarticular muscles, concerning complex multijoint movements have been documented in various studies in the last 15 years (Bobbert et al., 1994; Jacobs et al., 1996; van Ingen Schenau, 1989).

Running requires a different contribution of mono- and biarticular muscles to an extending knee joint moment then cycling (Savelberg et al., 2003). In cycling, the knee joint is more flexed during the loaded phase then in running which indicates that the VAS muscles work at longer lengths compared with running.

Savelberg et al. (2003) recognized a difference in need for the biarticular muscles to direct an external force in running and cycling. The higher peak moment and the larger optimum muscle length of the VAS muscles of cyclists compared with runners allow this muscle to generate more power in cycling. During cycling there is a reduced need for the RF to direct the external force. This shows how the human body adapts to changes. Van Ingen Schenau et al. (1992; 1995) show that, in an extending limb, the RF muscle is important for directing the external force forward. In cycling, this is the force on the pedal while in running the force is applied to the ground. In running a forward component of the external force is required during the first half of the stance phase to control posture. In cycling, a forward component of the force is necessary at top dead centre (Neptune and Hull, 1998; van Ingen Schenau et al 1995). As a consequence, the knee and hip joint angle patterns between running and cycling differ considerably at phases in which recruitment of RF muscle is required. It is likely that this affects the coordination between mono- and biarticular muscles (Savelberg et al., 2003).

In daily activities which include the lower extremities such as in walking, running, standing up and sitting down the hip and knee joints simultaneously flex or extend. The same counts for pushing and pulling tasks when using the upper extremity, as they involve simultaneous shoulder and elbow flexion or extension movements. For these movements, it is essential to realize that when the proximal end of a biarticular muscle acts synergistically on the joint it crosses, the distal end of the muscle acts opposingly at the other joint. For example, in leg extension, the HA act synergistically on the hip joint but opposingly on the extending knee joint, while the RF, an antagonist of the HA, acts synergistically on the knee joint but opposingly on the extending hip joint. The opposite counts for leg flexion (Kumamoto et al., 1994).

Kumamoto et al. (1994) perform a theoretical simulation analyses as well as actual arm robotic experiments in order to elucidate mechanical control properties of antagonistic pairs of biarticular muscles. They conclude that the existence of the antagonistic pair of biarticular muscles, as they occur in the thigh (RF and HA) could possibly contribute to the compliant properties of the multiarticular extremity, and to the independent control of position and force at the endpoint of the extremity, leading to smooth, fine and precise movements. Besides that, they hypothesize that the main function of the RF may be control rather than force transmission, due to its very small insertion area.

Van Bolhuis et al. (1998) investigated on the influence of the direction of an external force on muscular activity of upper limb muscles. They conclude that biarticular antagonists control the direction of the force at the end-effector; in other words, their activation does
not depend the movement direction but only on the direction of the force at the wrist. The monoarticular muscles showed significantly more EMG activity for movements in a specific direction, which equalled the movement direction corresponding to the largest shortening velocity of the muscle. The EMG activity decreased gradually for movements in other directions. This direction-dependent activation appeared to be independent of the direction of the external force (van Bolhuis et al. 1998).

In 2001 Hof wrote a technical note which was concerned with the external forces a single leg muscle produces. The reasoning presented can explain e.g. the differences in the activity of mono- and biarticular muscles in cycling.

For a static limb, the force exerted at the endpoint due to the force of a single muscle has been calculated. It turns out that there are marked differences in the action of mono- and biarticular muscles (Hof 2001). The action of a muscle results in a force $F$ that is exerted on the floor. In the reasoning to follow it is assumed that only one muscle works at one time.

Monoarticular muscles produce a directional force which is directed in the lengthwise direction of the limb. The force of biarticular muscles can have a markedly transverse component. The principal direction of this force is also the movement direction of the endpoint which is the most favourable for the muscle to do work (Hof 2001). Fig. 24 illustrates this.

Fig. 24 a: the external force produced by the So, Fig 24 b: the external force produced by the GA. The figure is derived from Hof 2001.

Fig 24 a and 24 b show the differences in forces produced by mono- (24a) and biarticular muscles (24b) in a static limb where only one muscle contracts at a time. It is shown that the force produced by the SO is one directional, following the lengthwise direction of the limb, while the force produced by the GA is multidirectional with a lengthwise, a horizontal and a vertical component. These findings might be an explanation for the different activation patterns described by e.g. Jones et al. during jumping. They show that biarticular muscles are able to direct an external force in various directions, a clear difference to monoarticular muscles. They, however show also that monoarticular muscles are also able to direct an external force, but their external forces are only one directional. So they can only exert their forces in one direction. These findings also support the hypothesis that we have to look at each movement or position separately when we want to analyse the role of a muscle. For the position and force shown in Fig 24a the so clearly is able to
produce and direct an external force. The difference between SO and GA is that GA is able to direct the force in more directions.

In his note Hof states similar results for GU, VA, RF and HA. The monoarticular muscles all produce one directional forces, while the biarticular muscles produce multidirectional forces.

One weakness of Hof’s investigation is that his results are derived from static simulations, neglecting friction and the weight of the body segments. Simulations that take this into account might find different results.

From an optimization approach performed on the upper limb Raikova (2000) investigates the functions of biarticular muscles compared to those of monoarticular muscles. His main conclusions are that it is impossible to formulate strict advantages of the biarticular muscles under quasistatic condition, their peculiarities depend on limb position, external loading and neural control. In general, monoarticular muscles are more powerful than biarticular ones; biarticular muscles fine tune muscles coordination, their control is more precise and graceful. The presence of biarticular muscles leads to an increase of joint reactions and moments, which leads to stabilization of the limb.

It can be assumed that biarticular muscle activity is indeed influenced by the direction of the external force (Jones et al., 2003; Kumamoto et al., 1994; Neptune et al., 1998; Savelberg et al., 2003; van Ingen Schenau et al., 1992; 1995; van Bolhuis et al. 1998).

However there is no general opinion about the role of monoarticular muscles. Hof 2001 writes that they are exerting a force to the external, however the question remains if this is an important aspect of their activation to control the direction of an external force. Bolhuis et al 1998 stated that their activity is corresponding to the direction in which they have the largest shortening velocity (van Bolhuis et al. 1998).

They further say that this direction dependent activation appeared to be independent of the direction of the external force (van Bolhuis et al. 1998). It is possible that monoarticular muscles add something to the direction of an external force if it fits to their preferred direction.

Relevance for physiotherapy

It would be possible to train patients with devices in which they have to transmit an external force into different directions. It has been shown in the previous chapter how a patient can be trained to exert a force with the upper limp. Another possibility would be a device in which a patient has to pull or push an object in a certain direction, as shown in Fig. 25. This would be also possible for the lower limb. An example for it is outlined in the Physiotherapy chapter.

Another possibility to train patients with lower limb pathology is illustrated in the Chapter about Physiotherapy.
Fig. 25: The patient’s task is to push the grey object in the indicated direction. The reaction force (ORF) of the object has a large extending moment at the shoulder and an almost negligible one at the elbow. They have to be overcome for example by the biceps. If the object has a different position the direction of the force is different and the activity of the biarticular muscles will change.
Chapter III

Coordination Strategies
The previous chapters of the current review deal with explaining the mechanisms of biarticular muscles occurring at the extremities. This chapter is concerned with the neurological aspect, meaning the actual cause and background of these mechanisms. A complete outline of coordination or motor control would be beyond the scope of this review. Our intention is to give the interested physiotherapist a brief outline of recently developed theories and research studies. Some of the research which has been carried out in the field of coordination is related to the research on the function of two-joint muscles.

It is suspected that there are principles behind coordination, like a underlying law or principle that makes the CNS choose for certain muscles in a certain task.

Considering the diversity of the musculoskeletal function, it is likely that a number of distinctly different criteria for muscle selection may be utilized for different activities (Crowninshield et al., 1981).

It has been shown that there is little variance in a subject’s muscular use for example during gait (Ivanenko et al., 2004) or for elbow movements (van Bolhuis et al., 1997). This indicates that always the same muscles are used to execute the same movement or task. It has been suspected that there might be a difference in the activation of mono- and biarticular muscles (van Ingen Schenau, 1989; Jones et al., 2003).

These assumptions are the reason why we have chosen to include a chapter about coordination in the current review. We want to answer the question if there is a real difference and if yes, what is the difference. In other words: If our CNS differentiates between mono- and biarticular muscles, what are the triggering factors? Why is there a difference? Firstly, we want to give the reader a brief outline of the principle of Motor control.

Outline for motor control:

The brain works hierarchically, meaning that there are higher centres in the brain and lower centres. Both are concerned with motor control. Motor control involves processing of sensory information, motor planning and execution of the movement.

An example: A person A is thirsty and wants to drink. A sees a bottle of water (sensory information) and reaches out for the bottle to grasp it (execution of the movement). Between these two events lies the processing of the information, the motor planning. This involves an estimation of the distance between the person and the object and an estimation of the necessary force that has to be used to lift it up (motor planning). It also involves selecting the right muscles to perform this task. This is outlined in Fig. 26.

![Fig. 26](image)

**Fig. 26** show a simplified principle of coordination.
Some movements do not fall under this principle, for example the reflexes. The patella tendon reflex, which is well known, is not controlled by the brain but is a spinal reflex. When your doctor hits your patella tendon some receptors in the tendon notice the elongation. This information is sent to the spinal cord which, in a reflex loop, causes a contraction of the knee extensors which causes the reaction which we see, i.e. the knee extends.

**Muscle redundancy:**

It is interesting to see that we have, for a given movement, more muscles than we would need. The number of muscles crossing a joint generally exceeds the degrees of freedom of this particular joint (Zhang et al., 2000).

Muscle redundancy, an excessive number of muscles compared to the mechanical degrees of freedom, provides the CNS with a wide range of choices of muscle coordination strategies in performing a given motor task. Consequently, researchers have come up with a series of different hypotheses concerning the organization of control of mono- and biarticular muscles.

For example, more than five muscles can contribute to flexion torque in the elbow joint. In order to achieve this flexion torque multiple muscle activation patterns are theoretically possible. We could use a different combination of muscles for the same movement, but we don’t do this. Studies on activation patterns have shown that for a given motor task more or less the same relative activation patterns exist among different subjects (Buchanan et al., 1993; Theeuwen et al., 1996; van Bolhuis et al., 1997). The observation of a more or less unique activation pattern for different motor tasks suggests the existence of underlying constraints, reducing the number of possible activation patterns for each task (van Bolhuis et al., 1998).

Nakazawa et al. (1994) conclude that different neural processes underlie the activation of mono- and biarticular muscles in the organization and control of movements.

**Global strategies:**

There are theories suggesting that muscle coordination originates from physiologically based criteria. The body might choose a certain combination of muscles for a certain task after a principle. For example the body wants to use its muscles so that fatigue is avoided as much as possible.

With EMG it is possible to measure when a muscle is active; however it is not possible to measure the actual force which a muscle produces during a movement. It is possible to record the activity of the biceps during flexing the elbow but it is not possible to record how much force the biceps produces.

However even the estimation of the activity is not exactly possible. Since signal strength in EMG activity is related to many factors (e.g. skin preparation, subdermal fat, subdermal muscle depth and contractile velocity) its presence should only temporarily be associated with muscle force predictions (Crowninshield et al., 1981).

It is possible to estimate the produced forces of a muscle, e.g. of the BIB during elbow flexion, with the help of simulation studies. It is, in these simulations also possible to investigate on the criteria for muscle activation.
How is this done? Suppose someone wants to investigate on the forces produced by the elbow flexors. First it is necessary to take an EMG of the movement that should be analysed, so in this case elbow flexion. Then one will try to simulate the given EMG pattern on a model, for example like the one we introduced in the first part of this review. In this model it is possible to simulate muscular activity and segmental movements, also muscle forces can be calculated. In the end one is able to state if the used criterion fits to the EMG recordings of the muscle activity or not. For example we could test whether during elbow flexion, the flexors are activated in a way that minimizes muscular fatigue, or if they are activated in order to have the least power output.

**Criterion of maximum endurance:**

One of the criteria is the criterion of maximum endurance described by Crowninshield et al. (1981). All optimization procedures, whether linear or nonlinear, require the assumption that the body selects muscles for a given activity according to a certain criterion, e.g. minimization of muscle fatigue (Crowninshield et al., 1981).

We suggest that the muscle selection, so as to maximize activity endurance, is physiologically reasonable during many normal activities, particularly prolonged and repetitive activities, such as normal gait (Crownshield et al., 1981).

The features of muscle coordination predicted by the criterion of Crowninshield and Brand seem to occur in a variety of motor tasks: in reflex responses during maintenance of posture, in normal locomotion in cats and humans, in locomotor movements elicited in animals with a transected spinal cord and in skilled motor tasks like cycling, load lifting, reaching movements and in the static tasks of producing endpoint forces (Prilutsky 2000).

For low-intensity, cyclic tasks such as locomotion, muscles are coordinated in such a way that endurance is maximized (Ait-Haddou et al., 2000).

However: one must be cautious when drawing conclusions about the validity of an optimization criterion based solely on muscle activity predictions even when temporally correlated with EMG. We have demonstrated that non-physiological criteria can predict reasonable muscle activity. Therefore, good agreement in muscle force predictions and EMG activity cannot alone be considered giving sufficient proof that the optimization criterion selected is the criterion which the body uses (Crowninshield et al., 1981).

The strategy of minimum muscle fatigue does seem to be a reasonable explanation for the reduction of activation patterns during both static and dynamic tasks.

**Control of joint moments:**

This section is more concerned with the location and the design of the motor control system.

It seems plausible that common features of muscle coordination in different movements originate from common neural control mechanisms (Prilutsky, 2000).

Prilutsky (2000) introduces a model for muscular control that will be described in the following section. He assumes there are different neurological centres for different joints. Take as an example the ankle and assume that there is one centre which controls ankle flexion and one which controls ankle extension. One-joint muscles are therefore connected to only one centre while two joint muscles are connected to two centres. The control centres are on the level of supraspinal motor systems. This is explained in Fig 27.
This means that the human body is equipped with a centre which controls all muscles that have a flexing moment at the ankle and one controlling all muscles that have an extending moment on the ankle. More excitation is given to the muscles that have a bigger moment. In the case of ankle extension the muscle receiving most excitation would be the triceps surae as it has the longest moment arm in relation to the joint axis.

The muscles are excited and inhibited by the centres in the following manner: antagonists either inhibit or excite each other; synergists inhibit each other hierarchically, meaning that the stronger muscles inhibit their weaker agonists and two-joint muscles inhibit one-joint muscles. The two-joint muscles can inhibit their agonists and activate their monoarticular antagonists for energy transfer and joint stiffness. Joint stiffness is the resistance of the joint to external forces that would alter the joint angle. The activation of monoarticular antagonists can prevent joint damage (anatomical constraint is fulfilled).

The role of biarticular muscles in coordination:

In this section we want to look at some studies that investigate the activation of mono- and biarticular muscles. What are the triggering factors for their activation? We are concerned with the role an external force plays, what is the influence of sensory information.

a) Direction of an external force:

One possible explanation for the reduction of the possible activation patterns was already introduced by van Ingen Schenau (1989) who suggest that the activation of biarticular muscles is related to the direction of a force exerted by the end-effector, meaning the most distal moving segment (e.g. the hand or foot). On the contrary, monoarticular muscles might be activated in relation to the movement direction. This hypothesis was supported by Jacobs and van Ingen Schenau (1992) and van Ingen Schenau et al. (1995).
This unique action of mono- and biarticular muscles would indeed reduce the number of possibilities to achieve a certain motor task.

However Jones et al. (2003) state that there might be no complete separation between the activation criteria for one- and two-joint muscles. In their study they conclude that the activity patterns in each jumping direction are dictated by other factors such as: the early initiation of appropriate forward momentum, the transition from countermovement to propulsion, the control of individual segment rotations, the control of the location of the ground reaction force and the direction and influence of the subsequent landing.

In other words their results suggest that there are other factors that do not allow us to differentiate completely between mono and biarticular muscles. The activation of the monoarticular muscles did not fit to the hypothesized role, while the biarticular muscles’ activity changed when the direction of the external force changed.

Although one could now state that biarticular muscle activity is indeed related to external forces it is still possible that there are other factors which influence them. This brings us to the hypothesis that each movement needs to be studied separately in order to make conclusions about the role of the structures involved. The functions may differ depending on which movement is performed.

b) Sensory information and biarticular muscle coordination:

Sensory information from muscle afferents seems to play a crucial role in the ability to adapt movements to different environments (Smeets, 1994). As sensory information is important in motor control one could raise the question: Is the activation of mono- and biarticular muscles related to sensory information, and if so, is there a significant difference between the activation of mono and biarticular muscles?

In a model study, Smeets (1994) examines the dependency of the accuracy of sensory and motor information on the biarticularity of muscles. This is done by comparing the behaviour of two sets of muscles in controlling multijoint arm movements. The study results show that the direction sensitivity is more constant for the biarticular muscle set than for the monoarticular muscle set.

It is therefore concluded that the model including biarticular elbow flexors and extensors appears to be advantageous in ensuring a good overall accuracy of the sensory information about the speed and direction of a movement. These accuracy considerations put an additional constraint on muscle coordination. This can explain differences in control strategies between situations which do not differ biomechanically from each other.

In our opinion, it might be interesting to think of the relation between sensory information and directing an external force. After all, the reaction force of an object or the ground will activate the sensory nervous system. When you push an object with your hand you feel this object. This information is transmitted to the CNS where it is, as all sensory information, processed and might play a role in motor planning.

During load lifting in which a combination of ankle extension, knee flexion and hip extension joint moments are required GA and HA have the agonistic action at both joints they cross. Their activation and predicted forces increase with increasing knee flexion moments and ankle and hip extension moments. RF has the antagonistic action at the knee and hip joint and its activation and predicted force are low.
The advantage of HA and GA muscles is the ability to produce moments at two adjacent joints simultaneously which allows for a reduction of total muscle force, stress and fatigue in the task of load lifting. RF on the other hand has the antagonistic action at both joints, and its activation in this situation is the most disadvantageous for the production of the required joint moments.

It is proposed that the functional significance of the specific coordination of biarticular muscles occurring in a back lift and other multi-joint tasks may be a reduction of the total muscle force, stress and fatigue.

The features of activation of biarticular muscles observed in the study of Prilutsky et al. (1998) are also shown for different static and dynamic tasks performed by the lower and upper extremities (Doorenbosch et al., 1995; Jacobs et al., 1992; Prilutsky et al., 1997; Sergio et al., 1994).

These studies suggest that coordination of two-joint muscles is similar across different static and dynamic tasks.

Relevance for physiotherapy:

It is difficult to establish a connection between motor control, biarticular muscles and physiotherapy. One reason for this is that there is no proof for different activation criteria for mono and biarticular muscles.

However, it remains possible that biarticular muscles play a role in motor control, if we again look at the criterion of maximum endurance. If biarticular muscles add to the energy efficiency of locomotion and this is an underlying criterion of motor control it might be beneficial to train these muscles. For an athlete performing endurance sports such as cycling or running, it may be advantageous to focus training on biarticular muscles. It may also be beneficial for athletes performing jumping sports. However, a jump is not a movement which requires endurance and the criterion behind coordination in jumping might be of another kind (e.g. maximum force output).

Bobbert et al. (1996) have found a connection between motor control, strength training and jumping. As there seems to be no conclusive evidence for a different motor control strategy of biarticular and monoarticular muscles we regard these findings as important.

He states that maximum jumping height is determined by the properties of the musculoskeletal system, but actual jumping height depends strongly on control. The practical implications for this knowledge is that exercises aimed at improving muscle properties should be combined with exercises which allow athletes to practice with their changed muscle properties and adapt their control.

What happens if control is not re-optimized?

This becomes relevant when we consider properties that can be changed in vivo by training, such as muscle strength. It has been shown that if muscle strength of a model was increased but control was not re-optimized, jumping height actually decreased rather than increased.

Jumping height was only shown to improve if the increase in muscle strength was followed by re-optimization of control.
Chapter IV

Relevance for physiotherapy
4.1 FINDINGS

Working with the human musculoskeletal system is probably the most important element of the physiotherapeutic profession. It is therefore essential to know as much as possible about the human body in order to achieve the best possible improvement through our therapy. However, the most current knowledge on the function of biarticular muscles seems to circulate only amongst scientists and is kept so complicated and theoretical that it is barely accessible for physiotherapists and is therefore of little value for physiotherapists. One of the main objectives of this review paper is to present this valuable knowledge in a comprehensible manner so that physiotherapists, who are not so familiar with scientific terminology, can profit from it.

The main conclusion that we can draw from the findings mentioned throughout this paper is that the musculoskeletal system is much more complicated than it is presented in anatomy books or anatomy lessons of physiotherapy studies. Anatomical knowledge is still mostly taught in a very simplified and therefore non-realistic manner. It has been shown that biarticular muscles have clearly distinct functions from monoarticular muscles, as they relate forces and moments of different joints with one another. Therefore it is not correct to regard them simply as two monoarticular muscles.

It is certainly beyond the scope of this paper to provide the reader with a detailed guide on how this knowledge can be applied to all fields of physiotherapy, especially as there is no literature available which connects this theoretical knowledge to the practical field of physiotherapy. However, we wish to at least give some ideas on how the knowledge on the functions of biarticular muscles may be applied to physiotherapeutic practice and on physiotherapy-related research.

Each chapter in this paper gives examples on how to apply their contents to physiotherapeutic situations. This chapter summarizes the most important unique functions of biarticular muscles which have been elucidated throughout this paper and gives a complete overview of the functions together with conclusions that we have drawn for the field of physiotherapy (Table 2). Furthermore, it includes a description of how biarticular muscle functions may provoke stereotypical locations of muscle injuries. We have developed an idea of a potential training device which we will elucidate and finally, we comment on future directions in the field of biarticular muscles which may be beneficial for physiotherapists.

1) The ability of biarticular muscles to transfer energy

The transfer of energy has been explained by means of the jump. The motions leading to a jump are very common and can be found in a lot of other motions. However, it has been shown to play a major role in many other movements of both the upper and the lower extremity as well. In order to achieve an optimal performance, no matter which movement it is, we need to keep in mind that several segments of the body are connected with each other, and therefore decreased performance can have different causes. This does not only apply to jumping but also to many other movements, both explosive and non-explosive. Decreased performance of all kinds of multijoint tasks can have several causes as the movement consists basically of a mechanical chain of actions taking place. The
aim of the physiotherapist should be to make a very precise examination in order to find the weakest link in the chain. This can only be achieved when employing an overall approach; in other words the patient should be seen as a whole and not restricted to his pathology. For example a decreased jumping performance could result from a weakness in the distally located muscles, such as the SOL or the GA. However, due the transfer of energy more proximally situated muscles such as the GU, RF or HA could play a role in this deficiency.

2) Contradictions of moments and movements

Biarticular muscles are able to solve contradictive situations between the moment and the movement occurring at a joint. This means that the movement which we see is not always performed by those muscles which, as we have learned, have the function of carrying out that particular movement. As already shown in the task of pushing in object into a certain direction (Fig. 19) elbow extension is performed by the biarticular elbow flexor (BIB). We need to keep this in mind when doing strength training, as we can easily go wrong and instruct our patients to perform inappropriate exercises for a specific muscle group. Another example for the occurrence of the contradiction between the moment and the movement occurring at a joint is illustrated below.

3) Biarticular muscles don’t have the main function of producing strength.

Large power outputs are mostly achieved by monoarticular muscles. Therefore, we conclude that when aiming at improving the performance of a certain task, one should first consider which mono- and which biarticular muscles contribute to this movement before setting up a training programme. When training monoarticular muscles one should emphasize on improving strength; the strength training of monoarticular muscles should concentrate on those parts of ROM in which the muscle can produce the most force. On the contrary, in the training of biarticular muscles one should put emphasis on improving coordination, fine-tuning and the quality of the movement rather than performing pure strength training.

The following table gives an overview of all the functions of biarticular muscles elucidated throughout this paper.

<table>
<thead>
<tr>
<th>Function</th>
<th>Findings</th>
<th>Conclusions / Relevance for PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy transfer</td>
<td>Connection of segments; coupling of joint moments; overall approach</td>
<td>Especially relevant for explosive movements such as jumping and sprinting (athletes). Proximally located MA muscles should be trained mostly with emphasis on strength increase, while distal muscles should be trained more dynamically, with less intensity. Cyclic movements, such as pedaling and walking should be performed fluently, not with frequent interruptions, as it may lead to decreased energy efficiency and accelerated fatigue.</td>
</tr>
<tr>
<td>Anatomical features</td>
<td>Long tendons, small muscle bellies</td>
<td>Indicates that main function is not the production of muscle force.</td>
</tr>
<tr>
<td>----------------------</td>
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<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Proximo-distal sequence; coupling of joint moments</td>
<td>Connection of segments</td>
<td>Leg press, weight lifting, jumping exercises. Training of the whole lower extremity; never isolated emphasis on one joint alone. The proximo-distal sequence may be disturbed.</td>
</tr>
<tr>
<td>Coactivation of MA agonists and BA antagonists</td>
<td>MA and BA muscles depend on each other</td>
<td>They cannot be strictly separated; however one should keep in mind that they have differing functions.</td>
</tr>
<tr>
<td>Coordination of the movement; direction of the external force</td>
<td>BA muscles do not have a preferred movement direction (PMD); they are activated in order to direct the external force. Other than MA muscles, BA muscles improve the quality of a movement.</td>
<td>More emphasis should be given to coordinative tasks. 3-dimensional tasks (as they require a large degree of coordination), such as pulley exercises, would most likely be a good exercise for BA muscles.</td>
</tr>
<tr>
<td>Muscle force</td>
<td>Not the main function of BA muscles; this is main function of MA muscles.</td>
<td>No isolated strength training for BA muscles; emphasis on coordination and stabilization.</td>
</tr>
<tr>
<td>Contraction moment-movement</td>
<td>The movement which we see is not always carried out by the muscles which have this function of performing this particular movement. Examples: Pushing an object across table in medio-ventral direction; leg press while exerting the force downward; specific jumping directions.</td>
<td>We need to think multi-dimensionally and let go of the idea of strict muscle functions which we have learnt from anatomy lessons. Different movement directions will train different muscles and require different coordination patterns.</td>
</tr>
<tr>
<td>Coordination</td>
<td>Possibly different coordination strategy for MA + BA muscles; hierarchy.</td>
<td>Coordination should be optimal; excessive strength training should always be followed by coordination training. Otherwise performance may be decreased.</td>
</tr>
<tr>
<td>Structural adaptations</td>
<td>BA + MA muscles adapt to certain situations. Athletes who specialize in a specific discipline may have differing muscle functions, depending on the task.</td>
<td>One should always see the patient as an individual; therefore, the treatment protocol should be adjusted accordingly.</td>
</tr>
<tr>
<td>Muscle injury</td>
<td>Avulsion fractures frequently occur at the origin or insertion of BA muscles when they are overloaded.</td>
<td>Particular injury patterns can be recognized and preventive training can help influence muscle coordination patterns in a positive way, so that the muscle stresses are decreased and injuries possibly prevented.</td>
</tr>
</tbody>
</table>

Abbreviations: BA: biarticular, MA: monoarticular
4.2 BIARTICULAR MUSCLE FUNCTIONS AND INJURIES

Are there typical locations of injuries due to the function of biarticular muscles? The location of avulsion fractures at the origin or insertion of biarticular muscles suggests that this may reflect the unique function of biarticular muscles. This is a finding of Kameyama et al. (1994) who analysed different mechanisms of avulsion fractures occurring at the insertion or origin of a muscle in young athletes. Before the epiphyses close, they are mechanically weak and may separate with violent muscular contraction. The location of the avulsion fracture mostly depends on the type of sports activity. 70% of fractures of the AIIS occur during kicking a ball as in football or rugby, 65% of the fractures of the ASIS occur during sprinting, and also 65% of the fractures of the tibial tuberosity occur during the vertical jump in basketball or high jumping. The following three factors give the explanation for the locations of these injuries:

1. When the force direction passes through or near the knee joint the hip joint will be more heavily loaded than the knee joint.

2. On the contrary, when the force direction passes through or near the hip joint the knee joint will be more highly loaded.

3. If explosive and excessive load is applied at the foot, the more highly loaded joint will collapse first. The collapsed joint may occasionally cause the fracture of the biarticular muscles which originates or inserts at the collapsed joint.

In the vertical jump the functional force line passes through the centre of the hip joint. Therefore the knee is more highly loaded than the hip. This is shown Fig. 28. Explosive and excessive stress applied in this period may result in an avulsion fracture at the distal knee joint, i.e. at the insertion of the RF.

![Fig. 28 shows the action line of the GRF in a vertical jump prior to push off. The force (F) passes the centre of the hip joint and the knee and ankle joint at some distance (dKJ and dAJ), putting higher load on these joints.](image)

Typical injury sites have also been shown for the motion of kicking a ball, which may lead to a fracture at the ischial tuberosity in inexperienced players. This may be due to
excessive eccentric contraction of the HA in order to decelerate the leg at both the hip and the knee joint. The VM shows a large amount of activity in experienced players which indicates that in unskilled subjects excessive stress is concentrated on the RF. During the follow-through motion, the leg is swung up and there is generally little activity in the BF and the GU. However, in unskilled subjects a strong activity of the BF is shown which may be explained by a counter-traction against the strong contraction of the RF. This muscular behaviour frequently leads to injuries at the ischial tuberosity (origin of the BF). Due to little research done in this field the findings should not be over-evaluated and care should be taken when drawing conclusions. Further research is necessary before one can generalize that certain biarticular muscle functions contribute to the occurrence of certain (sports) injuries. However, if the findings of Kameyama et al. (1994) could be confirmed it would play a major role in the prevention of injuries. Musculature could be trained in such a way that biarticular muscles are stressed as minimally as possible in order to prevent injuries.

4.3 REHABILITATION AND STRENGTH TRAINING MACHINES

In the development of machines designed for strength training in sports and rehabilitation biarticular muscles have commonly been seen as two monoarticular muscles. These devices are mostly one-dimensional, therefore suppressing the functions of biarticular muscles to transfer energy and develop their full capabilities. More two- and three-dimensional machines should be developed which enable a much more functional training of the musculoskeletal system. We are not saying that one-dimensional training devices are useless. In fact, they are very beneficial in the first stages of rehabilitation as they do not require such a large amount of muscular coordination and enable rehabilitation to commence shortly after the injury. However, as the patient improves, it is required to progress to two- and then three-dimensional movements in order to achieve maximal improvement. This is certainly a field of potential future research.

From the knowledge we have gained throughout this project we have developed an idea of a potential training device which is multi-dimensional and therefore can be adjusted to suit different requirements, enabling the patient to train more effectively and closer to a real-life situation than the conventional leg press.

The leg press is a strengthening device which is commonly used in the physiotherapeutic rehabilitation of the lower extremity and lower back. However, this machine we have in mind does not have a fixed foot rest (black block in figures 29a-c) but a mobile one which can be tilted backwards or forwards and raised or lowered.

As shown previously, in many situations of daily life we need to direct external forces in different directions. A good example is the jump, as its required movement pattern is similar to the one occurring when pushing a leg press. Different jumping situations, as they are required in sports, such as volleyball or basketball, could be simulated more easily with a machine designed in the manner described above.

The figures 29a-c show three possibilities of how this device may be adjusted. Fig. 29a shows the leg press as it known from fitness or rehabilitation centres. In this case, the exerted force F1 has a horizontal, i.e. straight forward direction which requires more or less equal hip and knee joint moments. In fig. 29b the foot rest is tilted backward and slightly raised, therefore F2 is directed forward and upward which requires a stronger knee
extending moment and at the same a small hip flexing moment. When the force $F_3$ (foot rest is tilted forward and slightly lowered) is directed forward and downward (fig. c) a large hip extending moment is required while only a small knee flexing moment is necessary.

![Diagram](attachment:image.png)

Fig. 29a shows extending hip and knee moments of equal strength; GM, VAS, RF and HA are able to contribute to positive work.

![Diagram](attachment:image.png)

In fig. 29b the small hip flexing moment, and large knee extending moments lead to a conflicting situation at the hip joint. RF assures a flexing moment at the hip and supports the monoarticular knee extensors; no eccentric contraction of monoarticular muscles is required.

![Diagram](attachment:image.png)

Fig. 29c shows a situation in which a strong hip extending moment and a small knee flexing moment is required; through HA activation both moments can be produced.

By adjusting the angle of the foot rest one can emphasize the load on one muscle or another. For example in fig. b) the load on the knee extensors is rather high, whereas activation of the hip extensors is not required. Fig. c) shows how the hip extensors can be stimulated more, due to a change in force direction.

Note that, also in the example of fig. 29c, a contradiction between the moment and the movement occurs at the knee joint. What we see is a knee extension, while in fact, due to the direction of the exerted force ($F_3$) the knee flexors, i.e. the HA, are active.

In the chapter direction of the external force we already mentioned a similar idea for the upper extremity where the direction of the external force can be directed differently through different joint angles.

We do agree that the most effective type of training is to train the movement itself which has to be improved. However, in order to specifically train a patient’s ‘weak points’ we do regard such multi-dimensional training devices as described above as a potential valuable
tool in the field of rehabilitation. These devices would be closer to reality than conventional
machines, such as the leg press, and therefore have the potential to train muscles more
specifically to suit each individual’s needs.

4.4 FUTURE DIRECTIONS

Generally, most studies in the field of human movement sciences concentrate only
on movements performed by healthy subjects. Rarely, the findings of studies are related to
the field of rehabilitation or physiotherapy. An exception is, for example, Bobbert (1996)
who relates his findings on structural alterations of the musculoskeletal system to training.
Much more of this will be necessary in the future, as after all physiotherapy plays an
important role in the healthcare sector. The fact that we nowadays already find budget cuts
in public healthcare puts an even bigger demand on us as physiotherapists to prove that
what we are doing is effective. In order to achieve this, the education of physiotherapists
should aim at showing students how essential research is for the reputation of our profession
in the medical field and at motivating them to consider carrying out such research in the
future.

For the benefit of the physiotherapeutic field, we recommend future research to
emphasise on subjects with specific pathologies in which the influence of this pathology on
the musculoskeletal system, and more specifically on the function of biarticular muscles, is
examined.

In our opinion, especially the function of energy transfer is a factor which needs to be
examined further as it holds a great potential of possibilities for physiotherapeutic
rehabilitation. We consider the following questions as being of special interest (using the RF and HA as
examples):
- How would an injury of the RF influence the energy transfer?
- How does the body compensate for this loss of function? Would other muscles, such as
  the VAS, be more active?
- As energy transfer is related to isometric contractions of muscles, would it be beneficial
  for an athlete or patient to train the transferring muscles isometrically?
- How would a pathology of the HA effect their ability
to decelerate knee extension prior
to maximal extension in the long run?

To date, anatomical education for physiotherapy students clearly neglects a large
variety of functions of biarticular muscles. However, current research shows that there are
some clearly distinct functions of biarticular and monoarticular muscles. We therefore regard
it as necessary to update the contents of anatomy lessons and to present the entire functions
of both mono- and biarticular muscles, to clearly differentiate the two from each other in
order to give the most complete picture of muscle anatomy according to current research.

Structural adaptations and muscle injury

In muscles that are used in a stereotypical fashion, muscle architecture and joint
kinematics seem to interact in such a manner that muscles produce near-maximal power
during normal use. Muscle architecture has also been shown to change with altered muscle
use or in the face of a new mechanical environment (Lieber et al., 2000)
Similarly, Savelberg et al. (2003) hypothesize that structural adaptations within the
musculature occur in people who specialize in a discipline, such as running or cycling. These
two disciplines impose very different requirements on the lower limb muscles. In cycling, the
knee joint is more flexed during the loaded phase than in running (Fig. 30).
Fig. 30 shows the difference in knee flexion angle during cycling (30a) and running (30b). The VAS muscles (black curved line) have to work in a different average length in cycling which requires structural alterations in the muscles anatomy.

This indicates that, in cycling, the VAS work at longer lengths compared with running (Fig. 30). Differences in length which differing knee joint angles would impose in the RF are compensated by differences in hip joint angles between runners and cyclists.

During running, the knee bends in the initial phase of stance. As a result, both VAS and RF muscles perform an eccentric contraction in running. This eccentric phase is absent in cycling. Furthermore, running requires a different contribution of mono- and biarticular muscles to an extending knee joint moment than cycling.

Besides for athletes who have specialised in a certain discipline, these muscular adaptations have also been shown to occur following immobilisation of a joint (Lieber et al., 2000). For physiotherapists, it may therefore be interesting to establish if and in which way these muscular adaptations have an influence on the functions of biarticular muscles.
V
Discussion and Conclusion
In the following we will come back to our research question which leaves us to discuss the following three aspects:

(1) the functions of biarticular muscles;
(2) the unique functions of biarticular muscles compared to monoarticular muscles;
(3) the application of the findings derived from current scientific literature to the practical field of physiotherapy.

In summary, these are the main findings concerning the functions of biarticular muscles:
Biarticular muscles transfer energy amongst segments. This function is especially important during explosive movements, such as the jump and sprint, but has also been shown to occur during dynamic, but non-explosive movements, such as walking, cycling, skating and running, during contact control tasks, such as moving an object across a table, and during static tasks. This idea seems to be generally recognized by scientists all over the world. In our opinion, there is enough evidence that this energy transfer is a true and very important function of biarticular muscles which occurs in a wide variety of upper and lower extremity tasks.

However, we regard the hypothesis that the ability of biarticular muscles to transfer energy may be more important than their function of producing energy themselves as a very audacious one and think that it requires more scientific support before full weight can be given to it.

Furthermore, biarticular muscles are able to overcome conflicts occurring between the moment and the movement at a joint, such as in the contact control task of moving an object across a table or pushing with both legs in a certain direction. This function, together with the ability to transfer energy amongst segments, is said to increase the energy efficiency of movements. However, there seems to be no clear opinion on whether biarticular muscles actually increase energy efficiency and performance or not. The findings mentioned above are in favour of an increased energy efficiency and performance while some studies conclude that a monoarticular system would be more efficient or equally efficient compared with a system containing both mono- and biarticular muscles. However, one of these studies may be criticised for its poor simulation methods, as calculations are carried out with an unrealistically small moment arm and no anatomical constraint is used in the model. Another study concludes that the ability of biarticular muscles to generate maximal forces is lower than for corresponding monoarticular muscles. In our opinion, this finding does not necessarily support the hypothesis that monoarticular muscles would increase the performance of certain tasks (such as jumping) as we must also consider the function of biarticular muscles to transfer energy which also contributes to energy efficiency.

Therefore, care should be taken in order to not misinterpret or over-evaluate these findings. We conclude that biarticular muscles have a reduced ability to generate maximal forces compared to monoarticular muscles but, due to other important functions, will still improve task performances compared to theoretical systems which are purely monoarticular. After all, God created nothing without a purpose.

Many findings on the functions of biarticular muscles can, according to our opinion, be summarized as improving the quality of a movement compared to an entirely monoarticular system. The existence of an antagonistic pair of biarticular muscles, as they occur in the thigh (RF and HA) may contribute to the compliant properties of the multiarticular extremity, and to the independent control of position and force at the endpoint of the extremity, leading to smooth, fine and precise movements. Besides that, it
has been shown that biarticular muscles are advantageous in ensuring a good overall accuracy of the sensory information about the speed and direction of a movement. It is hypothesized that the main function of the RF may be control rather than force transmission.

However, there seems to be a discrepancy between some authors concerning the hypothesis that biarticular muscles are responsible for directing the external force while monoarticular muscles only contract when they are in the position to shorten. Some, however only few, studies carried out on the upper extremity show that monoarticular muscles are also capable of directing the external force throughout a movement. Therefore we are unable to conclude that this is a function which applies exclusively to biarticular muscles. It seems that the functions of both mono- and biarticular muscles differ depending on the movement which is performed. It is also possible that inaccurate measurement tools lead to discrepancies in research results. However, we must admit that we are not experienced enough in the field of human movement sciences in order to give an objective judgement on the quality of the methods used in the reviewed literature.

Coordination

In general, researchers seem to agree that there must be some kind of constraint which reduces the redundant number of degrees of freedom of a joint. One explanation for a possible ‘constraint’ could be that different coordination strategies occur for mono- and biarticular muscles. However, due to the extremely large and deviating amount of theories and hypotheses currently circulating amongst scientists, it does not appear as though one overall coordination strategy exists which reduces the number of degrees of freedom of all joints and for all possible movements. Perhaps future research will bring the answer to the questions whether different coordination patterns exist for mono- and biarticular muscles and which constraints control the number of degrees of freedom of certain joints.

Generally, we can conclude that there are some functions which are performed by biarticular muscles only. However, some functions may be unique for one task but not unique, meaning that monoarticular muscles share the same ability, for another.

We think that it is more important to regard mono- and biarticular muscles as synergistic systems which are dependent on each other and also regard their functions as task specific instead of holding on to the idea of two entirely different muscle types and behaviours.

Relevance for physiotherapy

The most difficult part of the current review is to find a connection between the rather theoretical scientific findings and the practical field of physiotherapy. We have done our best to connect each of the functions of biarticular muscles to physiotherapy by giving one or more practical examples.

However, it must be clear that, although a lot of research has been carried out on this field, there still remain many movements and tasks which have not been analysed. Therefore, we are unable to make overall conclusions for every kind of movement.

One major aim of this paper is to express the complexity of the musculoskeletal system and the importance of functional anatomy. The 'schoolbook anatomy' which
physiotherapists are commonly familiar with is a very simplified version of reality.

In rehabilitation therapy and training one requires knowledge regarding adaptation mechanisms of muscles, as well as comprehension of muscle functions during certain motor tasks in order to achieve an optimal improvement of motor performance (Savelberg et al., 2003).

There is much more to know about the human body; realizing this is the first step to improving the quality of our treatments.

The next step is, of course, to acquire some of this rather complicated knowledge and finally to apply it to the field of physiotherapy.

I think we have made clear that there certainly is a relevance of the knowledge on the functions of biarticular muscles for physiotherapy. However, we believe that future research should focus on (larger sample sizes and) subjects with specific musculoskeletal impairments in order to examine whether the same functions of biarticular muscles apply for these patients as have been found for healthy subjects. The findings from the studies we have reviewed give an idea of how biarticular muscles should function; now we still need to know how they function in the presence of certain pathologies. But unfortunately, it seems to be a very long way before this is achieved.

**Conclusion**

From the results of the current review we can conclude that biarticular muscles play an important role in transferring energy amongst body segments. Apart from that, they are also able to solve contradictions between the moment and the movement occurring at joints. These characteristics may further lead to increased efficiency of movements of the human body.

To date, no evidence is had for the hypothesis that different motor control patterns exist for mono- and biarticular muscles. The function of distributing the moments over the joints and directing the external force which has been attributed to biarticular muscles only by some researchers also seems to apply to monoarticular muscles in certain tasks.

However, a great deal of the knowledge on the functions of biarticular muscles can be linked to the field of physiotherapy in many different ways, being of great value for this profession. Nevertheless, almost all research studies are presented in a very theoretical way, making it difficult to draw conclusions for therapy.

Physiotherapists would most likely profit more from experimental studies on biarticular muscles carried out on subjects with certain pathologies.

We regard this topic as indispensable for our profession and therefore hypothesize that finding clarity on the functions of biarticular muscles for common musculoskeletal related pathologies as well as answering the question of whether different motor control patterns exist for mono- and biarticular muscles would be of great value for physiotherapists. Perhaps, with further evidence, this knowledge on the functions of biarticular muscles might even find its place in the anatomy books of the future.


VI Summary

Background and Purpose. A lot of research has been conducted in the field of human movement sciences in search of a unique action of biarticular muscles. The purposes of this review are to summarize the current knowledge on biarticular muscles with emphasis on their importance for functional activities and to find a link between this rather theoretical knowledge and the practical field of physiotherapy.

Methods. A search was made using PUBMED, MEDLINE, ELSEVIER, PEDRO and GOOGLE (1981 - 2004) using the keywords “biarticular muscles”, “two-joint muscles”, “polyarticular muscles”, “coordination”, “motor control”, “energy transfer” and “van Ingen Schenau”. The quality of all relevant articles was established by means of a criteria list taken from the Yearbook of Medical Informatics (2002). Studies scoring at least of 66% were included in our review.

Results. Biarticular muscles have several differing functions compared with monoarticular muscles. In the first part of this paper the general definitions and terminology, as well as the anatomical features of biarticular muscles are outlined. Part two explains in detail the special functions of the biarticular muscles which play an important role throughout many different types of movements.

Biarticular muscles have been shown to transfer energy from one joint to another during many movements and seem to be the solution for solving contradictions in the moment and the movement occurring at a joint. They also have the ability to couple the moments between two joints. As two-joint muscles are able to accelerate and decelerate several body parts they can couple the acceleration or deceleration of the segments which they are attached to. Furthermore, two-joint muscles play a role in directing an external force to the environment.

All of these functions are illustrated with the help of everyday examples and furthermore, linked to the field of physiotherapy.

The third part of the current paper deals with the neurological background of the functions of biarticular muscles. A brief outline is given on the connection between coordination and muscle activation.

A fourth chapter summarizes the functions of biarticular muscles and gives some ideas why this knowledge may be of interest for physiotherapists. Furthermore, it includes recommendations for further research. From a physiotherapist’s point of view, a weakness of current research may be that to date studies are almost exclusively carried out on healthy subjects. It would be more beneficial for this profession to carry out research on certain patient categories in order to determine whether the same muscle functions apply to certain kinds of patients as they occur in healthy subjects. And if there is a difference, in what way these muscle functions may vary or adapt in the presence of a certain pathology.

In the field of strength training biarticular muscles are commonly treated as two monoarticular muscles. We regard this as a deficit in the rehabilitation of patients with musculoskeletal disorders and will therefore introduce an idea in which training could be performed in a more functional manner respecting the unique functions of biarticular muscles.

Discussion and Conclusion. Generally, we conclude that the musculoskeletal system is indeed much more complicated than it is commonly taught in the physiotherapeutic education. Anatomy lessons should present muscle actions and properties in a more functional way and clearly differentiate between mono- and biarticular muscles, as current research gives reason to do so.

Keywords: biarticular muscles, two-joint muscles, polyarticular muscles, coordination, motor control, energy transfer, van Ingen Schenau


**Websites**

1. [modtech@thwory.uwinnipeg.ca](mailto:modtech@thwory.uwinnipeg.ca)

2. [http://www.med.uni-heidelberg.de/mi/yearbook/quality_criteria.pdf](http://www.med.uni-heidelberg.de/mi/yearbook/quality_criteria.pdf)

**Pictures on title page and back cover:**

Appendix vermiformis
Coordination: Van Ingen Schenau (1988) defines “coordination” as the concerted action of muscles when performing a certain movement. As such, it is ultimately determined by timing, sequencing and amplitude of muscle activation.

Criterion: Throughout the review we will use the term “criterion” when we speak of the underlying principle of muscle coordination, or more precisely, the strategy of the generation pattern.

EMG: Two different types of EMG occurred in our selection of articles, the surface EMG and the intramuscular EMG. Due to its simplicity and ethical approval, surface EMG was almost always used to observe muscular activity. The electrodes were applied to the skin, over the muscle bellies, usually two thirds of the belly’s length from the distal end and approximately parallel to muscle fibers. Table 2 gives an overview of all the monoarticular and biarticular muscles which were studied by means of EMG in the articles included in our review.

Energy sink: eccentric muscle activity leading to a conversion of kinetic energy into heat

Force platform: is able to measure the ground reaction force which plays a role e.g. in jumping and running movements.

Forward dynamics: For applications such as simulations of normal objects one can use Newtonian mechanics (3 laws of Newton). The movements are calculated from the forces, such as force = mass x acceleration. The laws of Newton can be applied to rigid bodies by assuming that the forces are acting on the centre of mass of the objects. Assuming that the mass is equal, the second law becomes: force = mass x acceleration.

Inverse dynamics analysis: Van Ingen Schenau (1990) gives an explanation of the “inverse dynamical analysis” which is a commonly used method in human movement studies. In this method of analysis which was developed by Elftman (1939b) Newtonian equations of motion are used to calculate the net force and net moments occurring in the joints. By combining kinematics with the measured ground reaction force, net joint moments and powers can be calculated (Novacheck, 1998). The body is seen as a system consisting of four linked rigid segments. The head, arms and trunk (HAT) are fused to form one segment, the rest of the body is divided into thigh, shank and foot (see figure?). All of these segments are connected by hinge joints with one degree of freedom. The whole model therefore only represents the movements performed in the sagittal plane. The axes of the joints are located in the middle of the joints (see drawing). It is assumed that there is no loss of energy through friction in the joints and gravity and ground reaction force are neglected as far as possible. The segments of the body are connected with muscles (see Table 1). The term “inverse” expresses that the analysis uses the result of the movement and its effect on the environment (e.g. the ground reaction force) to calculate the responsible net moments. Extensor moments are termed “positive”. Flexor moments are termed “negative”.

8.1 Glossary
**Muscle models:** The Hill-model, or Hill-based models were commonly used muscle models in the studies we reviewed. They were used to estimate the contribution, i.e. the mechanical output of individual muscles / muscle groups. EMG and kinematics served as input to these models (Jacobs et al., 1996).

**Pattern:** A “pattern” is a specific order of muscle activation by the central command for a given task, hence movement.

**Subjects:** The number of subjects in the selected articles varied between 5 and 13?. Sometimes comparisons were made to animal behavior, e.g. frog, cat, horse (van Ingen Schenau, 1992). Most subjects were athletes, e.g. cyclists, runners or at least “skilled” in performing the task that was examined. The subjects’ age was not always mentioned but ranged from ? to ?? in those studies where it was included. Some articles used no subjects at all but based their findings simply on computer models and simulations. See also Table ? for an overview of the subjects included in the reviewed studies.

Many researchers combined an experimental part of their study in which a certain movement or activity was observed / analyzed on a number of subjects with a computer model. The experimentally measured kinematics and EMGs served as input to the model.

---

**8.2 METHODS OF RESEARCH**

In the following section we will discuss some of the research methods used in the studies we reviewed. We have neglected these methods throughout the paper as the authors of the current review share the opinion that it is beyond the scope of this paper to go into great detail on the methods used and it would also contribute to further complexity and disturb the readability of the paper. Now, we will concentrate on the most important and most commonly occurring methods of research only. For an overview of the methods see Appendix 10.2 of this paper.

There are a many difficulties that scientists may encounter when searching for an answer to the question on the function of biarticular muscles. For obvious ethical reasons in vivo studies of the human body are merely possible. Therefore it is necessary to develop models that represent reality as closely as possible. Even today, current research methods are unable to measure various musculoskeletal variables directly, such as the contribution of individual muscle forces during certain movements or reaction forces occurring throughout the body. These and other kinetic quantities are therefore based on estimations which are carried out by means of dynamical simulations.

As computer models are only able to simulate reality they cannot fully represent the human body. Many models are only two-dimensional and also human muscles are unable to be simulated in a one-to-one relationship.

**Hill models:** Commonly used models in biomechanical simulations are the Hill-type Models. They are attractive due to their computational simplicity and their close relation to commonly measured experimental variables. Nevertheless, only few experimental attempts have been made to test the validity of these models (Perreault et al., 2003). From their recent study they conclude that for large muscle excursions, such as those occurring during locomotion, the errors for naturally activated muscle typically exceed 50%. This supports their hypothesis that the Hill model errors are largest at low motor unit firing rates. This is an
important point of criticism as low motor unit firing rates occur during common activities of daily life. So it might very well be that the Hill model is not appropriate for the simulation of normal movement conditions.

Generally, many research studies we refer to in this paper made use of surface EMG and computer simulations (e.g. Prilutsky et al., 1997; Prilutsky et al., 1998; Prilutsky et al., 1994; Jones et al., 2003; Neptune et al., 2001; Raasch et al., 1999; Welter et al., 2000; Osu et al., 1999; Bolhuis et al., 1998; Riley et al., 1998; Happee et al., 1995; van Ingen Schenau et al., 1992).

**EMG:** In general, EMG assisted approaches appear to give better results than optimization procedures which do not take EMG activity into account (van Bolhuis et al., 1997). Its activity reflecting the activity of many motor units can be a useful measure of muscle activation, but only in a very limited and well specified task. For example, during movements, EMG recordings can only be compared for one type of muscle contraction such as either lengthening or shortening contractions. Interpretations of differences in EMG activity obtained in both shortening and lengthening contractions is to date not possible (Gielen, 1999). Another weakness of the EMG is the electromechanical delay. The EMG delay is especially prominent when analyzing dynamic tasks. There are multiple reasons for this:

- The excitation contraction coupling and muscle-tendon complex dynamics cause a time shift between EMG and joint moment patterns as well as changes in the muscle length and the rate of its change modify muscle contractile abilities and, in turn, can modify EMG-force and EMG-moment relationships (van Ingen Schenau et al., 1995; Vos et al., 1991; Prilutsky, 2000).

**Muscle properties:** Savelberg et al. (2003) conclude from their study that muscle lengths and ratios may differ between athletes of different disciplines, such as runners and cyclists. From these results it may be concluded that the fixed optimal muscle lengths and fixed ratios between muscles as are often used in simulation studies are inaccurate. In order to improve precision and quality of the results when establishing muscle lengths and ratios it may be necessary to consider the performance of sportive activities as well as other frequently performed activities such as professions which require a great deal of physical activity.

**Subjects:** The entire selection of articles we reviewed analyse the function of biarticular muscles in healthy, mostly young and athletic, subjects. Basically, this group of subjects excludes all patients with musculoskeletal impairments. As physiotherapists, we are particularly interested in the question how biarticular muscles function when they function abnormally in order to be able to draw conclusions for therapy. It would be interesting to know if and how coordination patterns change e.g. in older subjects and in the presence of certain injuries (e.g. ankle fractures, Achilles tendon ruptures, supraspinatus tendonitis) or neurological pathologies, such as hemiplegia and SCI and whether the findings correlate with the results of those studies performed on healthy subjects.

Sample sizes in the literature we reviewed were rather small, ranging between 4 and 20 subjects.
### 8.3 LITERATURE OVERVIEW

Table 3. Overview of the most important studies we reviewed, in alphabetical order

<table>
<thead>
<tr>
<th>First Author &amp; Year</th>
<th>Subjects</th>
<th>Analyzed Movement(s)</th>
<th>Muscles</th>
<th>Methods of analysis</th>
<th>Outcome Measures</th>
<th>Main Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bobbert et al. 1994</td>
<td>None; only computer model</td>
<td>Maximum height jumps</td>
<td>Biarticular: RF, HA, GA Monoarticular: GU, VL, VS, SOL</td>
<td>Forward dynamic simulation model; 2 DOF; 4 rigid segments Hill-type muscle model</td>
<td></td>
<td>Max. jump height depends on combination of moment arms of GA at knee and ankle; at a given moment arm at the ankle there is an optimal moment arm at the knee joint; Conclusion: there is an advantage in biarticularity of GA.</td>
</tr>
<tr>
<td>Bobbert et al. 1988</td>
<td>Ten male skilled volleyball players Age 23 +· 3</td>
<td>Countermovement jumps</td>
<td>Biarticular: GA, HAM, RF Monoarticular: GU, SO, VAS</td>
<td>EMG; Computer simulation</td>
<td></td>
<td>Proximo distal sequence is necessary to achieve max jump height, transportation of energy is required for the same reason</td>
</tr>
<tr>
<td>Caldwell 2000</td>
<td>None, comment to Prilutsky 2000</td>
<td>Datas used from cycling studies</td>
<td>Biarticular: RF, HA</td>
<td>EMG</td>
<td></td>
<td>The relationship between muscle activity and any given joint moment will depend on the exact role a muscle plays in that specific task.</td>
</tr>
<tr>
<td>Chabran et al. 1999</td>
<td>Six healthy subjects</td>
<td>Postural adjustments associated with voluntary wrist flexions and extensions</td>
<td>Polyarticular: ECR, FCU Biarticular: BIB TLO Monoarticular: DE, TLA, TLM</td>
<td>EMG, Simulation</td>
<td></td>
<td>APA (postural adjustments) are involved in segmental posture, their organization is similar to general APAs associated with whole body movements. The use of constant directional postural synergies well agrees with a simplification of the motor control according to Bernstein.</td>
</tr>
<tr>
<td>Crowninshield et al. 1981</td>
<td>none</td>
<td>Elbow isometric contraction Gait</td>
<td>Biarticular: BIB Monoarticular: BRA, BRD Leg muscles</td>
<td>EMG Simulation</td>
<td></td>
<td>Endurance as an optimization criterion shows good results for gait and elbow movements</td>
</tr>
<tr>
<td>De Lassanet et al. 1997</td>
<td>Underarm throw Overarm throw</td>
<td></td>
<td>Biarticular: BIB, TLA, TLO Monoarticular: PM, DEL p.s., BRD</td>
<td>Model Lagrange equations</td>
<td></td>
<td>The model predicts a different optimal technique for a Stroke with a light or a heavy tool.</td>
</tr>
<tr>
<td>Study</td>
<td>Subjects/Setup</td>
<td>Methods</td>
<td>Findings/Interpretation</td>
<td></td>
<td></td>
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<tr>
<td>Doorenbosch et al. 1995</td>
<td>10 healthy male subjects (age: 27±3.5 years; height: 1.89±0.3 m; weight: 80.7±5.5 kg)</td>
<td>Contact control leg tasks Biarticular: BF caput longum, ST, RF Monoarticular: GU, VM, VI EMG Dynamometer Motion analysis software Linked segment model</td>
<td>Two-way analysis of variance for repeated measurements test for possible differences during isometric and isokinetic conditions (p&lt;0.01); Student’s t-test for paired samples (p&lt;0.01); Strong relationship between activity difference RF-HA and moment difference: mean (±SD) correlation coefficients 0.935 (±0.027) and 0.930 (±0.033) for all isometric and isokinetic datapoints respectively. RF and HA muscles function in reciprocal way to regulate the distribution of net moments about joints, whereas activation of MA muscles appeared to depend on the type of task; Supports the hypothesis of energy minimization</td>
<td></td>
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</tr>
<tr>
<td>Doorenbosch et al. 1997</td>
<td>3 male, 2 female subjects (CCTs) Fast contact control leg tasks (CCTs)</td>
<td>Force plate Motion analysis software system Linked-segment model surface EMG</td>
<td>The action of RF and HA is consistent in controlling the direction of the external force; The actions of MA do not agree with their hypothesized role as simple work generators. This might suggest one out of more available strategies the CNS can use to control different CCTs.</td>
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</tr>
<tr>
<td>Dounskaia et al. 2002</td>
<td>9 right handed students, 18 to 31 years Horizontal, cyclical arm movements None, investigation joint torques Movement recorder OPTOTRAK Calculations; Computations for joint torques ANOVA to measure if the movement type has an influence on joint torques</td>
<td>Shoulder is controlled similarly in all movements; Elbow control is dependent on the direction of the movement</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Year</td>
<td>Sample Description</td>
<td>Methods</td>
<td>Findings</td>
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<tr>
<td>Fregly et al.</td>
<td>1996</td>
<td>10 recreational male cyclists (age 27 ± 1.8 y, height 1.80 ± 0.03m, a weight 738 ± 67 N)</td>
<td>Seated ergometer pedling, no individual muscles mentioned; only net muscle joint torques and non-muscular forces were investigated.</td>
<td>Mechanical power analysis derived from closed-form state-space dynamical equations; 3 DOF, two-legged dynamical model; Monark ergometer; Dynamical simulation was computed using a parameter optimization algorithm.</td>
<td>The net hip and knee muscle joint torques produce most of the energy needed to propel the crank during pedalling. Net ankle and hip extensor joint torques function &quot;synergistically&quot; to deliver energy to the crank during downstroke; net hip extensor joint torque generates energy to limb, while net ankle extensor joint torque transfers this energy from limb to crank. In contrast, net knee extensor and flexor joint torques function &quot;independently&quot; by generating energy to the crank through top and bottom of the stroke, respectively. Net ankle joint torque transfers and net knee joint torque generates energy to crank by contributing to the driving component of pedal reaction force. During upstroke, net ankle extensor joint torque transfers energy from the crank to the limb to restore the potential energy of the limb.</td>
<td></td>
</tr>
<tr>
<td>Gerbeaux et al.</td>
<td>1995</td>
<td>Three upper right limbs of cadavers</td>
<td>Elbow flexion and extension, biarticular: TLO, monoarticular: TLA</td>
<td>X-rays; Biomechanical study</td>
<td>The method of modelling is applicable to other joints and muscle groups.</td>
<td></td>
</tr>
<tr>
<td>Gielen et al.</td>
<td>1998</td>
<td>None review</td>
<td>Upper limb elbow movements, biarticular: BIB, monoarticular: BRD</td>
<td>EMG</td>
<td>There is a task dependent reduction of the number of degrees of freedom.</td>
<td></td>
</tr>
<tr>
<td>Happee et al.</td>
<td>1995</td>
<td>Model study</td>
<td>Fast goal directed arm movements in the sagittal plane</td>
<td>A three-dimensional model of bones and ligaments</td>
<td>For the movement studied, the thoracocapular muscles were shown to deliver about 40% of the energy required for the acceleration of the arm during anteflexion and about 22% during retroflexion.</td>
<td></td>
</tr>
<tr>
<td>Herzog et al.</td>
<td>1994</td>
<td>No subjects; two-dimensional model</td>
<td>2 energetically equivalent muscles a) only 1-joint muscles b) 1- and 2-joint muscles</td>
<td>Adaptation of optimization approach by Crowinshield and Brand (1981);</td>
<td>In situations with equal directions of resultant joint moments; In situations where joint moments are opposite, the system containing just 1-joint muscles is more cost effective than the model containing 2-joint muscles.</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Task</td>
<td>Biarticular Muscles</td>
<td>Monoarticular Muscles</td>
<td>Methodology</td>
<td>Results/Findings</td>
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<tr>
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<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Hof 2001</td>
<td>none</td>
<td>Static lower limb muscle contractions, cycling</td>
<td>Biarticular: RF, HA, GA</td>
<td>Monoarticular: IL, VA, SO</td>
<td>Simulation study</td>
<td>Monoarticular muscles produce an endpoint force that is onedirectional, while two joint muscles forces are polydirectional. This can explain differences in mono and biarticular muscle activity during cycling.</td>
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<td>Ivanenko et al. 2004</td>
<td>6 healthy subjects (4 males, 2 females), age 26 – 42 years</td>
<td>Gait</td>
<td>Biarticular and polyarticular: GA, RF, SART, BF, ST, TFL, LD, TRAP</td>
<td>EMG</td>
<td>Linked rigid chain model</td>
<td>EMG for individual muscles in gait has a great intersubject variance. Five factors are found to influence this; Limb kinematics show small difference</td>
</tr>
<tr>
<td>Jacobs et al. 1996</td>
<td>7 elite male athletes, primarily runners</td>
<td>Explosive one-legged jump and sprint push-offs</td>
<td>Film analysis</td>
<td>Biarticular muscles transfer energy from proximal to distal joints during explosive leg extensions: Action of BA muscles causes efficient conversion of body segment rotations into the desired translation of body centre of gravity.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jones et al. 2003</td>
<td>12 participants, involved in jumping sports (basketball, volleyball)</td>
<td>Maximal-effort counter movement jumps (CMJ) in vertical, forward, intermediate and backward directions</td>
<td>Biarticular: RF, HA, GA</td>
<td>Repeated-measures ANOVA</td>
<td>Data suggest a strategy of muscular coordination that does not fall strictly under MA / BA dichotomy as was hypothesized. The muscular coordination strategy shown enables max energy generation and transfer between joints for propulsion without interference from the task of controlling the direction of the jump.</td>
<td></td>
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</table>

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<tr>
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<td></td>
</tr>
<tr>
<td><strong>Kumamoto et al.</strong></td>
<td>None; only models and robots</td>
<td>Robotic arm movements on a horizontal desk</td>
<td>No specific names mentioned. Models: a) only monoarticular muscles; b) antagonistic pair of biarticular muscles.</td>
<td>Mechanical engineering model analyses, i.e. actual arm robotic experiments; Theoretical simulation analyses</td>
<td>The existence of the antagonistic pair of biarticular muscles could positively contribute to the compliant properties of the multiarticular extremity and to independent control of position and force at the endpoint of the extremity, leading to smooth, fine and precise movements. Therefore, the existence of an antagonistic pair of biarticular muscles on the thigh is necessary for precise control of position and force exerted at the foot. Main function of the RF may be control rather than force transmission, due to its small insertion area.</td>
<td></td>
</tr>
<tr>
<td><strong>Lu et al.</strong></td>
<td>Two patients with hip prosthesis</td>
<td>walking</td>
<td>Biarticular: RF, HA, GA Monoarticular: IL, GU, VA, SO, TA</td>
<td>Mathematical model EMG</td>
<td>The model encourages further development of models including frontal and transversal plane models.</td>
<td></td>
</tr>
<tr>
<td><strong>Nakazawa et al.</strong></td>
<td>8 neurologically normal subjects (age: 27.5 ± 2.2 years)</td>
<td>F/E elbow movements with 5 loading conditions (0; 0.65; 1.3; 1.95; and 2.6 kg)</td>
<td>Biarticular: BIB Monoarticular: BRD</td>
<td>Surface EMG (BRD, BIB)</td>
<td>ANOVA: Statistically significant differences (p&lt;0.05) in all but the no-loading condition; Post-hoc test: significant BRD/BIB differences (p&lt;0.05) between AG1 vs. AG2 in 0.65 and 1.3 kg loading conditions and between AG1 vs. ANT in all but the no-loading condition. Different neurological processes may underlie the activation of MA + BA muscles in organization + control of movements.</td>
<td></td>
</tr>
<tr>
<td><strong>Neptune et al.</strong></td>
<td>5 healthy males (height: 177.0 ± 10.4 cm; weight: 73.3 ± 12.0 kg; age: 22.2 ± 2.1 years)</td>
<td>Walking (average speed: 1.5 ± 0.2 m/s)</td>
<td>Biarticular: GA Monoarticular: SOL</td>
<td>Forward dynamics musculoskeletal model using SIMM; Rigid segments (leg: thigh, shank, patella and foot) 15 individual Hill-type musculotendon actuators</td>
<td>Throughout single-leg stance both SOL and GA provide vertical support; in mid single-leg stance SOL and GA have opposite energetic effects on leg and trunk to ensure support and forward progression of both leg and trunk; in pre-swing only GA contributes to swing initiation.</td>
<td></td>
</tr>
</tbody>
</table>
| Novacheck | 1998 | Athletes | Walking, running, sprinting | Biarticular: HA, RF, GA  
Monoarticular: | EMG Kinematics (sagittal, coronal, transverse plane)  
Force plate | Energy transfer from distal to proximal;  
Recommendations for improvement of biomechanical models |
|---|---|---|---|---|---|---|
| O Riley et al. | 1998 | Ten subjects with unilateral stiff legged gait | Stiff legged gait | Biarticular: RF, HA  
Monoarticular: VA  
Segmental analysis | Film  
Software model | RF activity during early swing acts to limit knee flexion and contributes to stiff legged gait. HA activity in early swing contributes to knee flexion. |
| Osu et al. | 1999 | Four subjects 23 – 34 years | Upper arm muscle contractions and upper arm movements | Biarticular: BIB, TLO  
Monoarticular: DEL, BRD, BLA, TLA | EMG | Biarticular muscles are not simply coupled with the innervation of elbow monoarticular muscles but also are regulated independently according to the required task. |
| Popescu et al. | 2003 | None, comment | Upper limb reaching movements | general | | |
| Prilutsky et al. | 1998 | 4 collegiate athletes (Am. football players), age 23 +/- 5 yr. | Barbell weight lifting using back lift technique | Biarticular: RF, HA, GA  
Inverse Dynamics Analysis  
2 DOF leg model  
4 linked rigid segments | Surface EMG  
Regression equations to determine rate of length changes in RF and HA during swing phase;  
Surface EMG | Muscle coordination in load lifting is consistent with the strategy of minimum muscle fatigue. |
| Prilutsky | 1998 | 4 healthy subjects: 2 m, 2 f | Walking  
Running | Biarticular: RF, HA | Inverse dynamics analysis  
Regression equations to determine rate of length changes in RF and HA during swing phase;  
Surface EMG | The activation of RF and HA in walking and running is likely to be not dependent on the modulation of cutaneous afferent receptors from the foot. |
| Prilutsky et al. | 1996 | Two human lower extremity models with different sources of mechanical energy; 10 young healthy males (body mass: 60-82 kg) | Walking  
Running | Model 1:  
Biarticular muscles: RF, HA, GA  
Monoarticular muscles: GU, IL, VAS, TA  
Model 2:  
11 monoarticular muscles | EMG Force plates (ground reaction force measurements)  
16-link, 3-dim. model  
Motion analysis software (HUMMOT)  
Inverse dynamics approach | Mechanical energy expenditure (MEE) of models with different sources of mechanical energy appeared to be different during certain periods of the swing phase. The magnitude of the difference was, however, relatively small. |
<table>
<thead>
<tr>
<th>Reference</th>
<th>Subjects</th>
<th>Tasks</th>
<th>Joint Muscles</th>
<th>Method</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prilutsky et al. 1997</td>
<td>unknown</td>
<td>Static lower limb movements</td>
<td>Biarticular: RF, HA, GA</td>
<td>EMG Simulation with musculoskeletal model</td>
<td>During control of an external force in pushing direction, more force is allocated to the muscles with the bigger lever arm and the bigger PCSA. This corresponds to the strategy of minimizing muscle fatigue.</td>
</tr>
<tr>
<td>Prilutsky et al. 1994</td>
<td>Five male subjects</td>
<td>Jumping, landing and running</td>
<td>Biarticular: RF, GA</td>
<td>Film Inverse dynamics simulation</td>
<td>Proximal one joint muscles produce energy, two joint muscles transfer energy. Distal proximo sequence in landing, proximo distal sequence in jumping.</td>
</tr>
<tr>
<td>Prilutsky 2000</td>
<td>None, response</td>
<td>None, response</td>
<td></td>
<td></td>
<td>It is concluded that the criterion of Crowninshield and Brand qualitatively predicts the basic coordination features of the major one and two joint muscles in a number of highly skilled, repetitive motor tasks performed by humans.</td>
</tr>
<tr>
<td>Prior et al. 2001</td>
<td>14 males</td>
<td>Eccentric contractions of quads</td>
<td>Biarticular: RF, Monoarticular: VA</td>
<td>MR (Magnetic reasoning) Changes in MVC (max voluntary contraction), muscle soreness, muscle volume and T2 levels were measured</td>
<td>4 muscles were equally activated during the contraction; RF suffered greater injury than VA. Conclusion: Muscle activation is not a unique determinant of muscle injury.</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Measurement</td>
<td>Biarticular</td>
<td>Monoarticular</td>
<td>Notes and Findings</td>
</tr>
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<tr>
<td>Raikova 2001</td>
<td>None; 3 models: 1) consisting of mono- and biarticular muscles; 2) and 3) consisting of monoarticular muscles only</td>
<td>Flexion / Extension of shoulder, elbow and wrist joints.</td>
<td>Biarticular: BIC, TLO, EDI, FCR&lt;br&gt; Monoarticular: DEL p.cl., DEL p. sp., COR, TMJ, BRA, ANC</td>
<td>3 upper limb models in 3 DOF; Equations of Equilibrium and Optimization Procedure; Numerical Experiments.</td>
<td>It is not possible to formulate strictly advantages of BA muscles. Their peculiarities of BA muscles depend on limb position, external loading and neural control; MA muscles are more powerful than biarticular ones; BA muscles fine tune muscle coordination, their control is more precise and graceful; Presence of BA muscles leads to an increase of the joint reactions and moments, and therefore stabilization of the limb.</td>
</tr>
<tr>
<td>Savelberg et al. 2003</td>
<td>10 runners (8m, 2f) who run &gt; 20 km / wk; 10 cyclists (8m, 2f) who ride at least 100 km / wk</td>
<td>Maximal isometric knee extensions on a dynamometer</td>
<td>Biarticular: RF&lt;br&gt; Monoarticular: VAS</td>
<td>Dynamometer (Cybex II); Data analysis: Model by Hawkins and Hull; Stepwise polynomial regression. Statistical analysis: For Δ VAS and Δ RF curves, minimal and maximal values were determined. For total extending knee joint moment, minimal and maxima values were assessed as well as hip and knee joint angles at which these occurred; differences for values between cyclists and runners: Student t-test</td>
<td>Maximal extending knee joint moment was not different between groups (p = 0,111); Maximal joint moments were generated at different knee joint angles for both groups (p = 0,043); Knee joint angle at which VAS muscles generate a max. moment differed between the groups (p = 0,032); significant difference in magnitude of VAS between both groups (p=0,008); descending RF cyclists have significantly larger optimal knee joint angle than ascending RF cyclists (p=0,034) and runners (p=0,011)</td>
</tr>
<tr>
<td>Source</td>
<td>Participants</td>
<td>Movements</td>
<td>Biarticular</td>
<td>Monoarticular</td>
<td>Methods</td>
</tr>
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</tr>
</tbody>
</table>
| Smeets 1994 | None; only models. | Arm movements in one plane | a) Biarticular set:  
- BIB, TLO  
- PEC, INF;  
b) Monoarticular set:  
- PEC, INF, BRA, TR (short head), | | Equations; Simplified models | The use of biarticular muscles instead of monoarticular elbow flexors and extensors is advantageous to ensure a good overall accuracy of the sensory information about the speed and direction of a movement. Accuracy considerations put an additional constraint on muscle coordination. This can explain differences in control strategies between situations which do not differ biomechanically from each other. |
| Van Bolhuis et al. 1998 | 5 subjects for each protocol | Voluntary slow wrist movements in horizontal plane | Biarticular:  
BIB, TLO  
Monoarticular:  
TLA, DPS, BRD | Surface EMG OPTOTRAK | One-sided Fisher-Pitman randomization test | BA muscles control the direction of force at the end-effector; Importance of BA muscles for movement efficiency; Activation of MA muscles is based on the information of the movement direction and fully depends on the force direction; Activation of BA antagonists is based on the required force direction, irrespective of muscle shortening or lengthening. |
| Van Ingen Schenau 1989 | Skilled subjects | Jumping Cycling Running | Biarticular:  
ST, RF, GA  
Monoarticular:  
GU, VM, SOL | Inverse dynamics analysis Film analysis  "Jumping Jack" Surface EMG | | Energy transfer; Proximo-distal sequence in ballistic movements; Co-activation of monoarticular agonists biarticular antagonists |
| Van Ingen Schenau et al. 1990 | Comparison to animals: cat, frog, horse (quadrupeds) | Jumping Cycling Pushing object over table Running (Quadrupeds) | Biarticular:  
HA, RF, GA, BIB  
Monoarticular:  
GU, VL, VM, SOL | Inverse dynamics analysis Surface EMG Film motion analysis | | Contradiction moment - movement; Energy transfer; Constraints |
<table>
<thead>
<tr>
<th>Van Ingen Schenau et al.</th>
<th>5 experienced cyclists</th>
<th>Cycling</th>
<th>Biarticular: RF, BF (caput longum), SM Monoarticular: GU, VL, VM, SOL, TA</th>
<th>Ergometer Film analysis Pedal force measurement Inverse dynamics analysis Surface EMG</th>
<th>Co-activation of monoarticular agonists biarticular antagonists Control of direction of external force Constraints Contradiction moment -movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welter et al.</td>
<td>Ten male subjects</td>
<td>See Bolhuis et al 1998</td>
<td>Biarticular: BIB, TLO Monoarticular: BRD, DPS, TLA</td>
<td>EMG Dutch shoulder elbow model Hill Type Muscle model</td>
<td>Data for both mono and biarticular muscles revealed a higher activation in concentric than eccentric contractions. Other criterions than force velocity relationship can be the explanation for changes in EMG.</td>
</tr>
<tr>
<td>Zhang et al.</td>
<td>Four male and one female subject</td>
<td>Isometric and submaximal elbow extension</td>
<td>Biarticular: TLO, BIB Monoarticular: TLA, TLM, ANC, BRD</td>
<td>Electrical stimulation, EMG</td>
<td>Moment distribution was not proportiona to PCSA, monoarticular muscles were favored for isometric contractions. The two joint head of the biceps was contributing significantly less to extension moments that the one joint heads. Absolute contribution of all muscles increased with increasing moments.</td>
</tr>
<tr>
<td>Zajac</td>
<td>None, review</td>
<td>Jumping Pedaling Walking</td>
<td>Monoarticular: GU, VAS, SO Biarticular: GA, HAM, RF</td>
<td>Dynamical simulations</td>
<td>Jump: high vertical velocity at lift of occurs desiarbly at full extension because of energy transfer, in pedaling synergistic ankle plantarflexion allows energy transfer, in walking eccentric quad activity decelerates the leg and accelerates the trunk</td>
</tr>
</tbody>
</table>

Comment: The columns show (from left to right): first author and year of publication, a short description of the subjects, the analysed movement(s), the mono- and biarticular muscles included in the study, the methods of analysis, outcome measures and the main findings. Abbreviations: monoarticular (MA); biarticular (BA), polyarticular (PA); for abbreviations of muscles see Table 1.
### Table 3. Overview of the most important studies we reviewed, in alphabetical order

<table>
<thead>
<tr>
<th>First Author &amp; Year</th>
<th>Subjects</th>
<th>Analyzed Movement(s)</th>
<th>Muscles</th>
<th>Methods of analysis</th>
<th>Outcome Measures</th>
<th>Main Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bobbert et al. 1994</td>
<td>None; only computer model</td>
<td>Maximum height jumps</td>
<td>Bicorticular: RF, HA, GA; Monocorticular: GU, VL, VAS</td>
<td>Forward dynamic simulation model; 2 D.O.F.; 4 rigid segments; Hill-type muscle model</td>
<td>Max. jump height depends on combination of moment arms of GA at knee and ankle; at a given moment arm at the ankle there is an optimal moment arm at the knee joint; Conclusion there is an advantage in bicorticuarity of GA.</td>
<td>Max. jump height depends on combination of moment arms of GA at knee and ankle; at a given moment arm at the ankle there is an optimal moment arm at the knee joint; Conclusion there is an advantage in bicorticuarity of GA.</td>
</tr>
<tr>
<td>Bobbert et al. 1998</td>
<td>Ten male skilled volleyball players; Age 23 ± 3</td>
<td>Countermovement jumps</td>
<td>Bicorticular: GA, HAM, RF; Monocorticular: GU, SO, VAS</td>
<td>EMG; Computer simulation</td>
<td>Proximal distal sequence is necessary to achieve max jump height, transportation of energy is required for the same reason</td>
<td>Proximal distal sequence is necessary to achieve max jump height, transportation of energy is required for the same reason</td>
</tr>
<tr>
<td>Caldwell 2000</td>
<td>None, comment to Pitkashy 2000</td>
<td>Data used from cycling studies</td>
<td>Bicorticular: RF, HA</td>
<td>EMG</td>
<td>The relationship between muscle activity and any given joint moment will depend on the exact role a muscle plays in that specific task.</td>
<td>The relationship between muscle activity and any given joint moment will depend on the exact role a muscle plays in that specific task.</td>
</tr>
<tr>
<td>Chadain et al. 1999</td>
<td>Six healthy subjects</td>
<td>Postural adjustments associated with voluntary wrist flexions and extensions</td>
<td>Polycorticular: FCR, FCU; Bicorticular: BIB, TLO; Monocorticular: DE, TLA, TLM</td>
<td>EMG, Simulation</td>
<td>APA (postural adjustments) are involved in segmental posture, their organization is similar to general APAs associated with whole body movements. The use of constant directional postural synergies well agrees with a simplification of the motor control according to Bernstein.</td>
<td>APA (postural adjustments) are involved in segmental posture, their organization is similar to general APAs associated with whole body movements. The use of constant directional postural synergies well agrees with a simplification of the motor control according to Bernstein.</td>
</tr>
<tr>
<td>Crowninshield et al. 1981</td>
<td>None</td>
<td>Elbow isometric contraction; Gaer</td>
<td>Bicorticular: BIB; Monocorticular: BRA, BRD; Leg muscles</td>
<td>EMG; Simulation</td>
<td>Endurance as an optimization criterion shows good results for gait and isometric movements.</td>
<td>Endurance as an optimization criterion shows good results for gait and isometric movements.</td>
</tr>
<tr>
<td>Dr. Laussenet et al. 1997</td>
<td>Underarm throw; Overarm throw</td>
<td>Contact control leg tasks</td>
<td>Bicorticular: RF, caput longum, ST, RF; Monocorticular: GU, VM, V</td>
<td>EMG; Dynamometer; Motion analysis software; Linked segment model</td>
<td>Two-way analysis of variance for repeated measurements test; Two-way analysis of variance for repeated measures; Strong relationship between activity difference RF-HA and moment difference: mean (±SD) correlation coefficient 0.85 (± 0.03) and 0.93 (± 0.02); Several isometric and isokinetic datasets were used; 2 DOF; 4 rigid segments; Hill-type muscle model</td>
<td>Two-way analysis of variance for repeated measurements test; Two-way analysis of variance for repeated measures; Strong relationship between activity difference RF-HA and moment difference: mean (±SD) correlation coefficient 0.85 (± 0.03) and 0.93 (± 0.02); Several isometric and isokinetic datasets were used; 2 DOF; 4 rigid segments; Hill-type muscle model.</td>
</tr>
<tr>
<td>Doorenbosch et al. 1995</td>
<td>10 healthy male subjects; Age 27 ± 3.5 years; Height 1.80 ± 0.03 m; weight: 80.7 ± 5.5 kg</td>
<td>Contact control leg tasks (CCTs)</td>
<td>Bicorticular: RF, caput longum, ST, RF; Monocorticular: GU, VM, V</td>
<td>EMG; Dynamometer; Motion analysis software; Linked segment model</td>
<td>Two-way analysis of variance for repeated measurements test; Two-way analysis of variance for repeated measures; Strong relationship between activity difference RF-HA and moment difference: mean (±SD) correlation coefficient 0.85 (± 0.03) and 0.93 (± 0.02); Several isometric and isokinetic datasets were used; 2 DOF; 4 rigid segments; Hill-type muscle model</td>
<td>Two-way analysis of variance for repeated measurements test; Two-way analysis of variance for repeated measures; Strong relationship between activity difference RF-HA and moment difference: mean (±SD) correlation coefficient 0.85 (± 0.03) and 0.93 (± 0.02); Several isometric and isokinetic datasets were used; 2 DOF; 4 rigid segments; Hill-type muscle model.</td>
</tr>
<tr>
<td>Doorenbosch et al. 1997</td>
<td>3 male, 2 female subjects; Age 27 ± 3.5 years; Height 1.80 ± 0.03 m; weight: 80.7 ± 5.5 kg</td>
<td>Fast contact control leg tasks (CCTs)</td>
<td>Force plate; Motion analysis software system; Film analysis; Linked-segment model surface EMG; Surface EMG</td>
<td>Two-way analysis of variance for repeated measurements test; Two-way analysis of variance for repeated measures; Strong relationship between activity difference RF-HA and moment difference: mean (±SD) correlation coefficient 0.85 (± 0.03) and 0.93 (± 0.02); Several isometric and isokinetic datasets were used; 2 DOF; 4 rigid segments; Hill-type muscle model</td>
<td>The action of RF and HA is consistent in controlling the direction of the external force; The actions of MA do not agree with their hypothesized role as simple work generators. This might suggest one out of more available strategies the CNS can use to control different CCTs.</td>
<td>The action of RF and HA is consistent in controlling the direction of the external force; The actions of MA do not agree with their hypothesized role as simple work generators. This might suggest one out of more available strategies the CNS can use to control different CCTs.</td>
</tr>
<tr>
<td>Dounskaia et al. 2002</td>
<td>9 right-handed students; 18 to 31 years</td>
<td>Horizontal, cyclical arm movements</td>
<td>Scan; Investigation joint torques</td>
<td>Motion recorder; OPTOTRAK; Calculations; Computations for joint torques</td>
<td>ANOVA to measure if the movement type has an influence on joint torques</td>
<td>ANOVA to measure if the movement type has an influence on joint torques.</td>
</tr>
<tr>
<td>Frigly et al. 1996</td>
<td>10 recreational male cyclists; Age 27 ± 1.8 years; Height 1.80 ± 0.03 m; weight: 73.8 ± 6.7 kg</td>
<td>Seated ergometer pedaling</td>
<td>No individual muscles mentioned; only net muscle joint torques and non-muscular (e.g. centripetal and gravity forces) were investigated</td>
<td>Mechanical power analysis derived from closed-form state-space dynamic equations; 3 D.O.F.; two-legged dynamical model; Monarch ergometer; Dynamical simulation was</td>
<td>The net hip and knee muscle joint torques produce most of the energy needed to propel the crank during pedaling.</td>
<td>The net hip and knee muscle joint torques produce most of the energy needed to propel the crank during pedaling.</td>
</tr>
<tr>
<td>Year</td>
<td>Subjects</td>
<td>Experiments</td>
<td>Analysis</td>
<td>Description</td>
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<tr>
<td>1994</td>
<td>None; only 2-dimensional models</td>
<td>Static lower limb muscle contractions, cycling</td>
<td>Simulation study</td>
<td>Monarticular muscles produce an endpoint force that is unidirectional, while two joint muscles forces are multidirectional. This can explain differences in mono and biarticular muscle activity during cycling.</td>
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<tr>
<td>2001</td>
<td>6 healthy subjects (4 males, 2 females) age 20 – 42 years</td>
<td>Coxa</td>
<td>EMG</td>
<td>TA, PERI. IL, VA, SO, OE, Gmed.</td>
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<tr>
<td>2004</td>
<td>7 elite male athletes, primarily runners</td>
<td>Explosive one-legged jump and sprint push-offs</td>
<td>Factor analysis</td>
<td>TA, PERI. IL, VA, SO, OE, Gmed.</td>
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<tr>
<td>1996</td>
<td>2 participants, involved in jumping sports (basketball, volleyball)</td>
<td>Maximal-effort counter movement jumps (CMJ) in vertical, forward, intermediate, and backward directions</td>
<td>Film analysis</td>
<td>Film analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>6 elite male athletes, primarily runners</td>
<td>Robotic arm movements on a horizontal desk</td>
<td>Repeated measures ANOVA</td>
<td>Data suggest a strategy of muscular coordination that does not fall strictly under MA / BA dichotomy as was hypothesized. The muscular coordination strategy shown enables maximal energy generation and transfer between joints for propulsion without interference from the task of controlling the direction of the jump.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>None; only models and robots</td>
<td>Robotic arm movements on a horizontal desk</td>
<td>Mechanical engineering model analysis</td>
<td>The existence of the antagonistic pair of biarticular muscles could positively contribute to the compliant properties of the multiarticular extremity and to independent control of position and force at the endpoint of the extremity, leading to smooth, fine and precise movements. Therefore, the existence of an antagonistic pair of biarticular units on the thigh is necessary for precise control of position and force exerted at the foot. Main function of the RF may be control rather than force transmission, due to its small magnitude.</td>
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<tr>
<td>Study</td>
<td>Participants</td>
<td>Conditions</td>
<td>Methods</td>
<td>Analysis</td>
<td>Comments</td>
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<tr>
<td>Lu et al. 1997</td>
<td>Two patients with hip prosthesis</td>
<td>Walking</td>
<td>Biarticular: RF, HA, GA</td>
<td>EMG</td>
<td>Mathematical model. The model encourages further development of models including frontal and transversal plane models.</td>
<td></td>
</tr>
<tr>
<td>Nakazawa et al. 1994</td>
<td>8 neurologically normal subjects (age: 27.5 ± 2.2 years)</td>
<td>F/E: elbow movements with 3 loading conditions (0; 0.65; 1.5; 1.95; and 2.6 kg)</td>
<td>Biarticular: BIB</td>
<td>Surface EMG (BIB), BIB</td>
<td>ANOVA: Statistically significant differences (p&lt;0.05) in all but the no-loading condition; Post-hoc test: significant BIB/BIB differences (p&lt;0.05) between AG1 vs. AG2 in 0.65 and 1.3 kg loading conditions and between AG1 vs. ANT in all but the no-loading condition. Different neurological processes may underlie the activation of MA + BA muscles in organization + control of movements.</td>
<td></td>
</tr>
<tr>
<td>Neptune et al. 2001</td>
<td>5 healthy males (height: 177.7 ± 1.0 cm; weight: 73.3 ± 12.0 kg; age: 22.2 ± 2.1 years)</td>
<td>Walking (average speed: 1.5 ± 0.2 m/s)</td>
<td>Biarticular: GU</td>
<td>Forward dynamics musculoskeletal model using SIMM; Rigid segments (leg: thigh, Shank, patella and foot) 15 individual Hill-type muscle-tendon actuators</td>
<td>Throughout single-leg stance both SOL and GA provide vertical support; in mid single-leg stance SOL and GA have opposite energetic effects on leg and trunk; to ensure support and forward progression of both leg and trunk; in pre-swing only GA contributes to swing initiation.</td>
<td></td>
</tr>
<tr>
<td>O’Riley et al. 1998</td>
<td>Ten subjects with unilateral stiff legged gait</td>
<td>Stiff legged gait</td>
<td>Biarticular: RF, HA</td>
<td>Film</td>
<td>Regression equations to determine early swing activity in unilateral participants.</td>
<td></td>
</tr>
<tr>
<td>Osu et al. 1999</td>
<td>Four subjects (23 – 34 years)</td>
<td>Upper arm muscle contractions and upper arm movements</td>
<td>Biarticular: BIB, YLD</td>
<td>EMG</td>
<td>Biarticular muscles are not simply coupled with the intervention of elbow monoarticular muscles but also are regulated independently according to the required task.</td>
<td></td>
</tr>
<tr>
<td>Poppesssa et al. 2003</td>
<td>None</td>
<td>Upper limb reaching movements</td>
<td>General</td>
<td>Neuroanatomical and biomechanical properties are unlikely to be used for regulating voluntary motion, and that other control strategies, most notably the use of feedforward controllers in which muscles act as force generators acting primarily on inertial loads, are more consistent with their observations.</td>
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<tr>
<td>Prusnky et al. 1998</td>
<td>4 collegiate athletes (Am. football players), age 23 +/- 3 yr.</td>
<td>Barbell weight lifting using back lift technique</td>
<td>Biarticular: RF, HA, GA</td>
<td>Surface EMG; Inverse Dynamics Analysis 2 DOF leg model 4 linked rigid segments</td>
<td>Muscle coordination in fast lifting is consistent with the strategy of minimum muscle fatigue.</td>
<td></td>
</tr>
<tr>
<td>Prusnky 1998</td>
<td>4 healthy subjects: 2 m, 2 w</td>
<td>Walking</td>
<td>Biarticular: RF, HA</td>
<td>Inverse dynamics analysis; Regression equations to determine rate of length changes in RF and HA during swing phase; Surface EMG</td>
<td>Muscle coordination in fast lifting is consistent with the strategy of minimum muscle fatigue.</td>
<td></td>
</tr>
<tr>
<td>Prusnky et al. 1996</td>
<td>Two human lower extremity models with different sources of mechanical energy; 10 young healthy males (body mass 60-82 kg)</td>
<td>Walking</td>
<td>Model 1: Biarticular muscles: RF, HA, GA</td>
<td>EMG</td>
<td>Mechanical energy expenditure (MEF) of models with different sources of mechanical energy appeared to be different during certain periods of the swing phase. The magnitude of the difference was, however, relatively small.</td>
<td></td>
</tr>
<tr>
<td>Prusnky 2000</td>
<td>None</td>
<td>Static tasks, Dynamic tasks, Dynamic control tasks and reaching movements, Responses to postural perturbations, locomotion</td>
<td>Biarticular: HA, RF, GA, amongst others</td>
<td>Review</td>
<td>A conceptual scheme of connections between motorneuron pools of one and two joint muscles is proposed.</td>
<td></td>
</tr>
<tr>
<td>Target article</td>
<td>Static lower limb movements</td>
<td>Biarticular: RF, HA</td>
<td>EMG</td>
<td>Simulation with musculoskeletal model</td>
<td>Comparing EMG with computer predictions</td>
<td>During control of an external force in pushing direction, more force is allocated to the muscles with the bigger lever arm and the bigger PCSA.</td>
</tr>
<tr>
<td>Authors</td>
<td>Subjects</td>
<td>Protocol</td>
<td>Baricentric RF, GA</td>
<td>Film</td>
<td>Inverse dynamics simulation</td>
<td>This corresponds to the strategy of minimizing muscle fatigue</td>
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</tr>
<tr>
<td>Prinsky et al. 1994</td>
<td>Five male subjects</td>
<td>Jumping, landing and running; Energy transverse and relation of joint moments with direction of external forces</td>
<td>Baricentric RF, GA</td>
<td>Film</td>
<td>Inverse dynamics simulation</td>
<td>Proximal one joint muscles produce energy, two joint muscles transfer energy Dorsal proximo-distal sequence in landing, proximo-distal sequence in jumping</td>
</tr>
<tr>
<td>Prinsky 2000</td>
<td>None, response</td>
<td>None, response</td>
<td></td>
<td></td>
<td></td>
<td>Dorsal proximo-distal sequence in landing, proximo-distal sequence in jumping</td>
</tr>
<tr>
<td>Prior et al. 2001</td>
<td>10 cyclists (8m, 2f) who ride at least 100 km / wk</td>
<td>Arm movements in one plane 1) and 3) consisting of monoarticular muscles only 2) and 3) consisting of biarticular muscles:</td>
<td>Baricentric RF, GA</td>
<td>None</td>
<td>3 upper limb models as 3 DOF Equations of Equilibrium and Optimization Procedure; Numerical Experiments.</td>
<td>It is concluded that the extinction of Crowninshield and Brand qualitatively predicts the basic coordination features of the major one and two joint muscles in a number of highly skilled, repetitive motor tasks performed by humans.</td>
</tr>
<tr>
<td>Savelberg et al. 2003</td>
<td>10 runners (8m, 2f) who run &gt; 20 km / wk</td>
<td>Maximal isometric knee extensions on a dynamometer</td>
<td>Baricentric RF, GA</td>
<td>None</td>
<td>3 upper limb models as 3 DOF Equations of Equilibrium and Optimization Procedure; Numerical Experiments.</td>
<td>It is concluded that the extinction of Crowninshield and Brand qualitatively predicts the basic coordination features of the major one and two joint muscles in a number of highly skilled, repetitive motor tasks performed by humans.</td>
</tr>
<tr>
<td>Smeets 1994</td>
<td>None; only models. Arm movements in one plane</td>
<td>Arm movements in one plane a) Baricentric set: - Biarticular: BB, TLO, PFC, BRD - Monarcicular: PEC, INF, BRA, TR (short head), b) Monarcicular set: - PEC, INF, BRA, TR (short head), Equations; Simplified models</td>
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<td>The use of biarticular muscles instead of monoarticular elbow flexors and extensors is advantageous to ensure a good overall accuracy of the sensory information about the speed and direction of a movement. Accuracy considerations put an additional constraint on muscle coordination. This can explain differences in control strategies between situations which do not differ biomechanically from each other.</td>
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<tr>
<td>Van Bolhuis et al. 1998</td>
<td>3 subjects for each protocol</td>
<td>Voluntary slow wrist movements in horizontal plane</td>
<td>Baricentric RF, GA</td>
<td>Surface EMG OPTOTRAK</td>
<td>One-sided Fisher-Fisian randomization test</td>
<td>MA muscles control the direction of force at the end-effector, Impotence of BA muscles for movement efficiency. Activation of MA muscles is based on the information of the movement direction and fully depends on the force direction. Activation of BA antagonists is based on the required force direction, irrespective of muscle shortening or lengthening</td>
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<tr>
<td>Van Ingen Schenau</td>
<td>Skilled subjects</td>
<td>Jumping, Cycling</td>
<td>Baricentric RF, GA</td>
<td>Inverse dynamics analysis</td>
<td>Film analysis</td>
<td>Dorsal proximo-distal sequence in ballistic</td>
</tr>
</tbody>
</table>

**Document Details:**
- **Subjects:**
  - Five male subjects
  - None, response
  - 10 cyclists (8m, 2f) who ride at least 100 km / wk
  - 10 runners (8m, 2f) who run > 20 km / wk
  - None; only models.
  - None; only models.
  - 3 subjects for each protocol
  - Skilled subjects
- **Protocols:**
  - Jumping, landing and running; Energy transverse and relation of joint moments with direction of external forces
  - None, response
  - Arm movements in one plane
  - Voluntary slow wrist movements in horizontal plane
  - Jumping, Cycling
- **Baricentric RF, GA, Films:**
  - Baricentric RF, GA
  - Film
  - Inverse dynamics simulation
- **Other:**
  - Dorsal proximo-distal sequence in landing, proximo-distal sequence in jumping
  - It is concluded that the extinction of Crowninshield and Brand qualitatively predicts the basic coordination features of the major one and two joint muscles in a number of highly skilled, repetitive motor tasks performed by humans.
<table>
<thead>
<tr>
<th>Year</th>
<th>Subjects</th>
<th>Movement(s)</th>
<th>Monoarticular Muscles</th>
<th>Biarticular Muscles</th>
<th>Methods of Analysis</th>
<th>Outcome Measures</th>
<th>Main Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>Running</td>
<td>GU, VM, SOL</td>
<td>“Jumping Jack” Surface EMG</td>
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<td>Contradiction moment - movement; Energy transfer; Constraints</td>
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<tr>
<td>Van Ingen Schenau et al. 1990</td>
<td>Comparison to animals: cat, frog, horse (quadrupeds)</td>
<td>Jumping Cycling Pushing object over table Running (Quadrupeds)</td>
<td>Biarticular HA, RF, GA, BIB Monoarticular GU, VI, VM, SOL</td>
<td>Inverse dynamics analysis Surface EMG Film motion analysis</td>
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<tr>
<td>Van Ingen Schenau et al. 1992</td>
<td>5 experienced cyclists</td>
<td>Cycling</td>
<td>Biarticular RF, BF (caput longum), SM Monoarticular GU, VI, VM, SOL, TA</td>
<td>Ergometer Film analysis Pedal force measurement Inverse dynamics analysis Surface EMG</td>
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<tr>
<td>Welter et al. 2000</td>
<td>Ten male subjects</td>
<td>See Bolhuis et al 1998</td>
<td>Biarticular BIB, TLO Monoarticular BRD, DPS, TLA</td>
<td>EMG Dutch shoulder elbow model Hill Type Muscle model</td>
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<tr>
<td>Zhang et al. 2000</td>
<td>Four male and one female subject</td>
<td>Isometric and submaximal elbow extension</td>
<td>Biarticular TLO, BIB Monoarticular TLA, TLM, ANC, BRD</td>
<td>Electrical stimulation, EMG</td>
<td>Moment distribution was not proportional to PCSA, monoarticular muscles were favoured for isometric contractions. The two joint head of the biceps was contributing significantly less to extension moments than the one joint heads. Absolute contribution of all muscles increased with increasing moments.</td>
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<tr>
<td>Zajac 2002</td>
<td>None, review</td>
<td>Jumping Pedaling Walking</td>
<td>Biarticular GU, VAS, SO</td>
<td>Biarticular GA, HAM, RF</td>
<td>Dynamical simulations</td>
<td>Jump: high vertical velocity at lift of occlusal dissiably at full extension because of energy transfer, in pedaling synergistic ankle plantarflexion allows energy transfer, in scaling eccentric quad activity decelerates the leg and accelerates the trunk.</td>
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</tbody>
</table>

Comment: The columns show (from left to right): first author and year of publication, a short description of the subjects, the analysed movement(s), the mono- and biarticular muscles included in the study, the methods of analysis, outcome measures and the main findings. Abbreviations: monoarticular (MA); biarticular (BA); polyarticular (PA); for abbreviations of muscles see Table 1.