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Provider CPD 21418 (UK)
CE Broker ID 50-54885 (Florida USA)
Provider ECM 1701 (IT)
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Vector Analysis

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1. Linear and non-linear physics and mathematics in the musculoskeletal system

Understanding the musculoskeletal system requires a dual mathematical–physical approach.

In this text, linear physics and mathematics are used for the analytical study of individual body regions, while non-linear approaches are used for systemic analysis.

This methodological distinction represents the foundation for accurate and scientifically rigorous clinical evaluation.

2. Linear mathematics: the foundation of regional analysis

In mathematics, the term *linear* indicates a direct and proportional relationship between two functions.

Linear algebra is the branch of mathematics that studies vectors, vector spaces, linear transformations, and systems of linear equations.

A system is defined as linear when its components can be decomposed and recomposed and when an increase in one variable corresponds to a proportional increase in another.

This proportionality allows precise prediction of the effect of a muscular force on a specific skeletal structure.

Linear systems are described by simple equations that admit analytical solutions.

Linear algebra is used to study all "linear" physical phenomena, meaning those in which distortion, turbulence, and chaotic phenomena are not involved.

Linear mathematics, by *approximating the system*, provides a representation of reality that allows its functioning to be understood.

Although simplified, this approximation offers the clinician a powerful diagnostic tool for identifying the primary causes of joint deformity.

The musculoskeletal biomechanical analysis proposed here involves transforming muscle bundles into lines of tensile force, to which their vector actions on skeletal components are applied.

This vector-based analysis translates anatomical complexity into mathematical models that are interpretable and clinically applicable.

Muscles act exclusively through tensile forces, pulling their insertions closer together.

There are no muscles that push or function as levers.

Levers, of any type, imply orthogonal forces that no muscle can generate.

When the elbow flexes, there is no lever action but rather a tensile force that brings the distal insertion closer to the proximal one, like a hinge closing through cable traction.

Some anatomical structures act as force multipliers (malleoli, patella), but these are pulleys that redirect the direction of traction, not levers.

Joint rotations do not arise from pushing forces or lever systems, but from the application of tensile forces whose line of action does not pass through the joint axis.

In these cases, muscular traction generates a rotational effect around the joint axis, according to the same physical principles governing all rotational phenomena.

3. Non-linear mathematics: the key to systemic interpretation

While linear mathematics implies a proportional relationship between stimulus and effect, non-linear mathematics allows large variations to result from small signals.

This principle explains how apparently minor dysfunctions may generate complex clinical patterns and symptoms seemingly disproportionate to the triggering cause.

Alterations that would be considered negligible in linear mathematics may become relevant in non-linear mathematics when considering overall system behaviour.

Clinically, this explains why small muscle shortenings or mild asymmetries may, in some individuals, present with significant and widespread symptoms.

3.1 Complex systems in the human body

Non-linear mathematics studies real behaviours through general interpretative models.

Among its many components, particular reference is made here to the characteristics of complex systems, which are addressed in detail in the systemic section of the text.

A *complex system* is any system composed of more than one element or subsystem and presents several fundamental characteristics:

- all elements are interdependent and interact with one another
- any musculoskeletal alteration, even if localised, inevitably influences the entire body system
- understanding the functioning of a complex system is only possible by considering the system as a whole

Traditional segmental approaches are therefore insufficient for comprehensive diagnosis.

A complex system, in pursuing its objectives, is capable of generating solutions that cannot be predicted from examination of individual elements.

Clinically, this means that the nervous system develops compensatory patterns that cannot be deduced from analysis of individual muscle components.

A complex system uses energy most efficiently when operating at the *edge of chaos*, where stability and adaptability are balanced so that small signals can modify the system's state with minimal energy expenditure.

In biomechanical terms: when Working Capacity prevails over Resistant Force.

4. Methodological integration for clinical diagnosis

By integrating the two forms of mathematics, it becomes possible to analytically study local functional mechanisms while simultaneously gaining systemic interpretative tools regarding factors regulating statics and dynamics.

This integration is the core of the proposed diagnostic approach: local vector analysis provides the precision required to identify the involved structures, while systemic interpretation explains the consequences for the entire body.

The vector analysis presented here represents the first level of biomechanical investigation, essential for identifying the muscles primarily responsible for skeletal misalignments.

This two-dimensional analysis forms the necessary basis for understanding fundamental mechanisms and is progressively extended to three-dimensional and full systemic analysis, in accordance with non-linear mathematics.

Mastery of these foundational concepts is essential before proceeding to more complex analyses, as each level of complexity builds upon the previous one.

5. Foundations of vector analysis in biomechanics

5.1 Definition and characteristics of the vector in applied physics

In physics, a vector is a geometric entity characterised by three elements:

- **Magnitude**: its intensity, graphically represented by the length of the segment. Clinically, this represents the amount of muscular force expressed.
- **Direction**: the line on which the vector lies, anatomically corresponding to the muscle's line of force.
- **Sense**: the orientation along the line, represented by an arrow, indicating the direction of muscular action from origin to insertion during contraction.

A vector is represented by an oriented segment from A to B and is termed *vector* because, in a sense, it carries A to B.

Fig. 01 – All three vectors share the same direction but differ in magnitude: AB > EF > CD. Blue and red vectors have the same sense; the green vector has the opposite sense.

5.2 The parallelogram rule

The parallelogram rule allows calculation of the resultant of two or more vectors.

This mathematical principle enables prediction of the movement resulting from combined muscle actions and, conversely, identification of the muscles responsible for an observed deformity.

In systems with multiple acting forces, the global resultant is obtained by summing forces pairwise, always applying the parallelogram rule.

This methodological approach ensures reproducibility and objectivity in clinical evaluation.

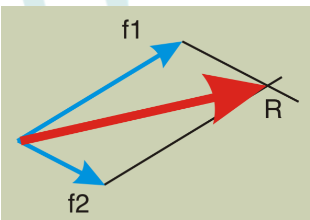


Fig. 02 – Given two (or more) vectors f1 and f2, applying the parallelogram rule allows calculation of the resultant R.

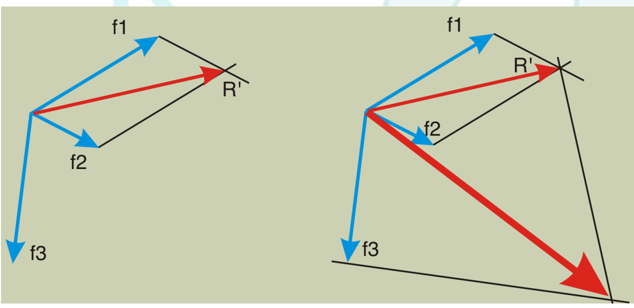


fig. 03: In systems with multiple vectors, to arrive at the overall resultant, they are summed two by two always applying the parallelogram rule

The parallelogram rule is also used to calculate the intensity one or more vectors must express to balance another, depending on spatial arrangement.

This application clarifies muscular compensatory mechanisms.

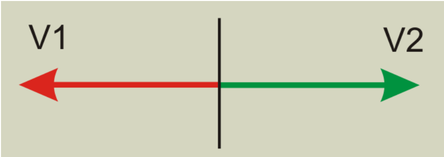


fig. 04: vector V1 is balanced by vector V2 having the same magnitude but opposite

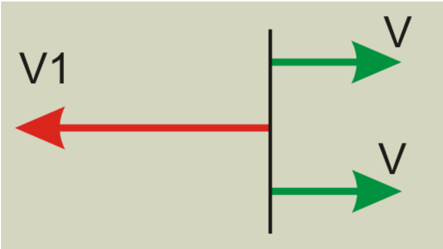


fig. 05: vector V1 is balanced by two or more vectors V having opposite direction and whose modular sum equals the magnitude of V1

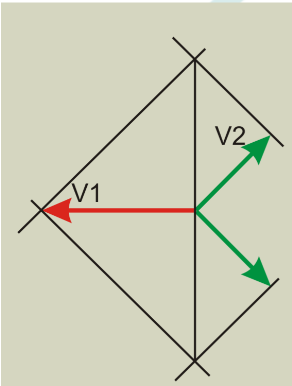


fig. 06: Applying the parallelogram rule, vector V1 is balanced by two oblique vectors, V2 and V3, having equal magnitude and equal angular deviation

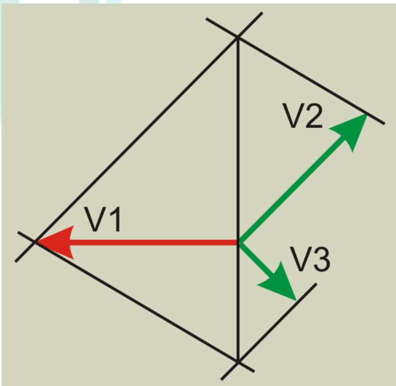


fig. 07: Applying the parallelogram rule, vector V1 is balanced by two oblique vectors, V2 and V3, having asymmetric magnitude and angular deviation

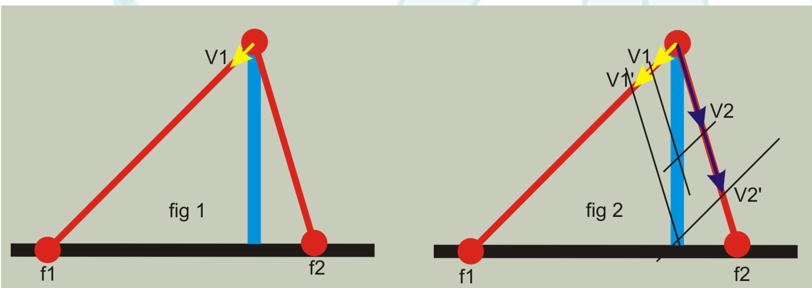


fig. 08: Given a force f1 expressed by vector V1 applied to an unconstrained rod (fig. 1), applying the parallelogram rule it is possible to calculate the intensity of vector V2 required by force f2 to balance vector V1 (fig. 2) in order to keep the rod vertical. Due to the different obliquity of the lines of force, vector V2 must express an intensity that is more than double that expressed by V1. Every increase in the magnitude (intensity) of vector V1 requires a linear modular increase of vector V2

6. Vector representation of the muscular system

In the figures, muscles are not represented anatomically but according to their lines of force, to which vectors are applied.

This simplification focuses analysis on biomechanical mechanisms, excluding anatomically irrelevant details for vector study.

The muscle line of force is defined by fibre orientation.

Vectors may be represented as resultants or decomposed into components.

Vector forces determine alterations of joint axes.

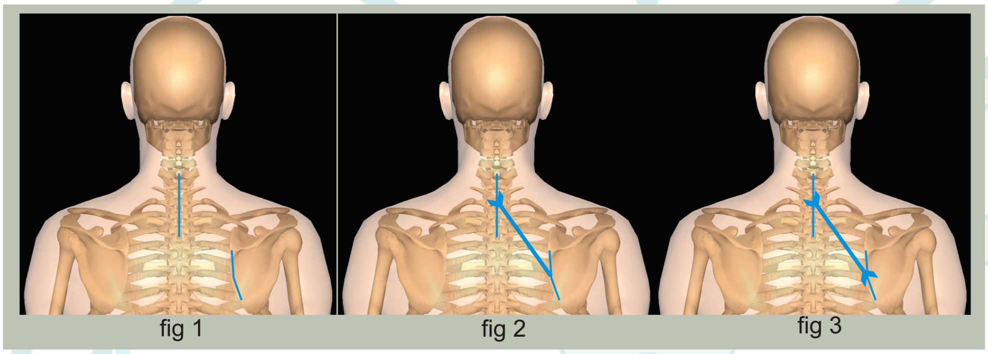


fig. 09: Graphically, a straight or curved line segment will be used to indicate insertions (fig. 1), a segment with an arrow at the base to indicate the mobile point of the muscle's line of force (fig. 2), a segment with arrows at the base to indicate the muscle's lines of force in the absence of fixed points (fig. 3).

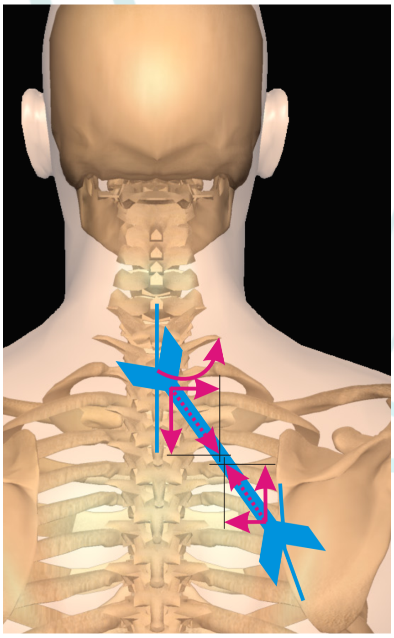


fig. 10: Straight or curved segments with arrows will be used to indicate the resulting vectors on the skeleton as a consequence of muscle shortening. In the example, the skeletal movements induced by the rhomboids in the absence of fixed points. Vector decomposition shows the greater vertical component compared to the horizontal one. Consequently, the vertical components will elevate the scapula and cause lateral compression to the intervertebral discs; the horizontal components will adduct the scapola, while on the vertebrae from C6 to D4 they will cause ipsilateral vertebral convexity and contralateral rotation of the bodies.

7. Force couples and resulting moments

A single resultant is not always obtained, particularly in three-dimensional analysis. When at least two resultants are present, a *force couple* exists.

In joint mechanics, the term *moment* corresponds to torsional moment, meaning the rotational effect produced by a force—or force couple—applied at a distance from the joint axis.

Force couples generate resultant moments.

The overall moment is calculated as the sum of each force magnitude multiplied by its half-distance.

Moments determine joint rotations and localised load concentrations.

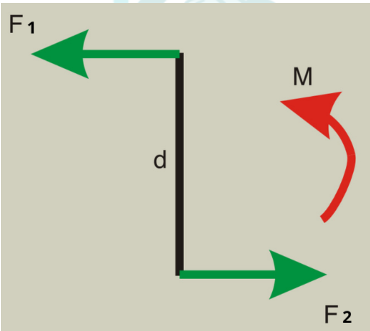


fig. 11: Two forces F1 and F2 applied to a rod at distance d from each other, create a resulting rotational moment M given by the sum of the two individual moments M1 and M2 determined by the product of F1 and F2 by the half-distance ½ d. M1 = F1 x ½ d; M2 = F2 x ½ d; M = M1 + M2

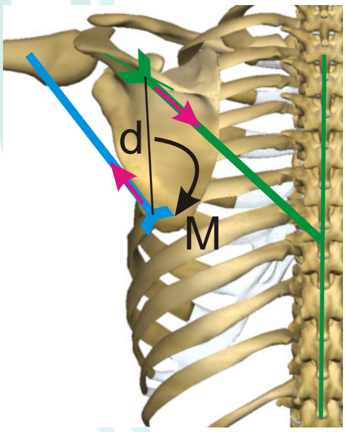


fig. 12: The force couple exerted on the scapula by the lower fibers of the trapezius (green) and the teres major (blue), at distance "d" from each other, creates a rotational moment M on the scapula.

8. The nature of muscular traction on insertions

Applying vector logic to muscles requires recognising that muscles act by approximating insertions through tensile forces.

During contraction, the muscle pulls its insertions closer together.

This is especially evident in polyarticular muscles and those inserting on mobile skeletal segments.

Monoarticular muscles with insertions on relatively fixed structures (e.g., the pelvis) may be analysed as forces with a single predominant direction.

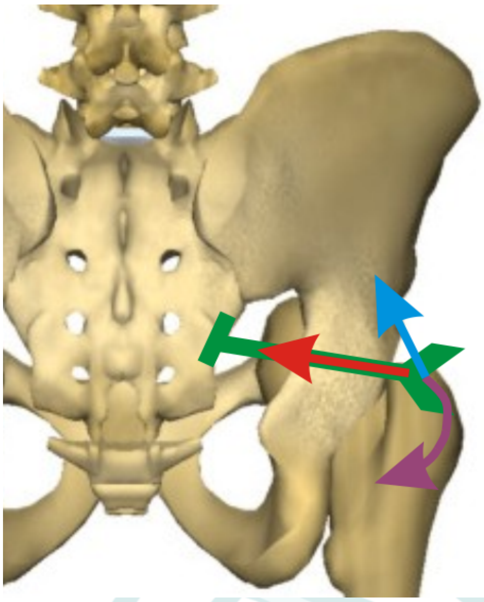


fig. 13: Transforming the piriformis muscle according to its line of force (in green), it is possible to consider the sacral insertion as a fixed point and the femoral insertion as a mobile point. The main vector (in red) determines the compaction of the femur into the acetabulum. Vector decomposition (procedure not shown) gives rise to a vector (in blue) having a modest abductory action on the femur and a vector (in purple) having a mild external rotatory action on the femur. The main action of mono-articular muscles is joint stability while, having modest vector components, they are entirely secondary in determining active movement. They behave as active ligaments capable of adapting to endo-articular stresses

9. Vector analysis of polyarticular muscles

Examining a large polyarticular muscle such as the latissimus dorsi, vector decomposition reveals multiple potential actions.

Different skeletal alterations arise depending on which force lines are predominantly involved in shortening.

This functional variability explains why a single muscle may be responsible for apparently different clinical presentations.

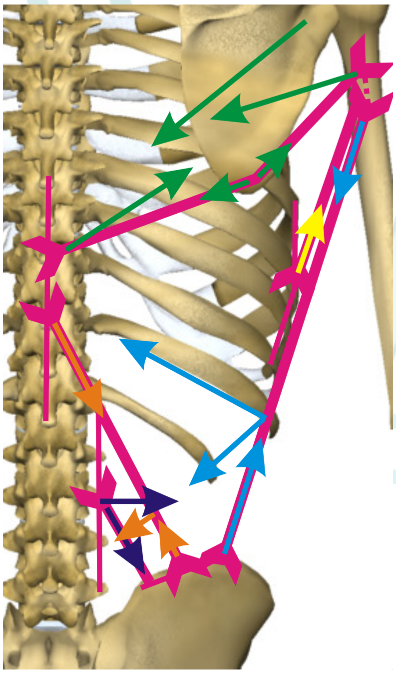


fig. 14: In purple the lines of force of the latissimus dorsi - quadratus lumborum couple. The segments with arrows indicate the vector resultants divided by color. As shown in the drawing, many act on the skeleton in opposite directions. As we will see in the chapter on latissimus dorsi patterns, depending on the vector predominance of individual lines of force, we will have different skeletal alterations.

10. Vector equilibrium and joint axiality

Joint axiality is ensured not only by capsuloligamentous structures but also by balanced muscular forces.

Even a single excessive force component may induce compensatory tone increase in antagonist muscles.

Minor vector imbalances can trigger widespread compensatory mechanisms that, over time, lead to progressive structural changes.

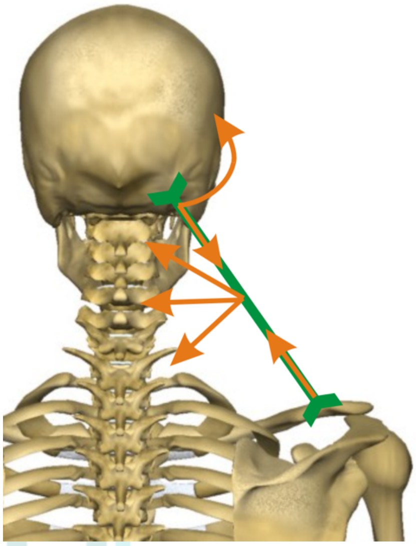


fig. 15: Transformation of the upper trapezius fascicle (in green) along its line of force. Since the cranial and clavicular insertions are not "absolute" fixed points, if the muscle is in contraction, contracture, or shortened due to excess tone in the contractile portion, or has residual shortenings in the connective tissue portion of the fibers, potentially the resulting vectors (in orange) are capable of: elevating the ipsilateral shoulder girdle; tilting the cranium ipsilaterally; extending the cranium posteriorly and rotating it contralaterally; translating the cervical vertebrae contralaterally.

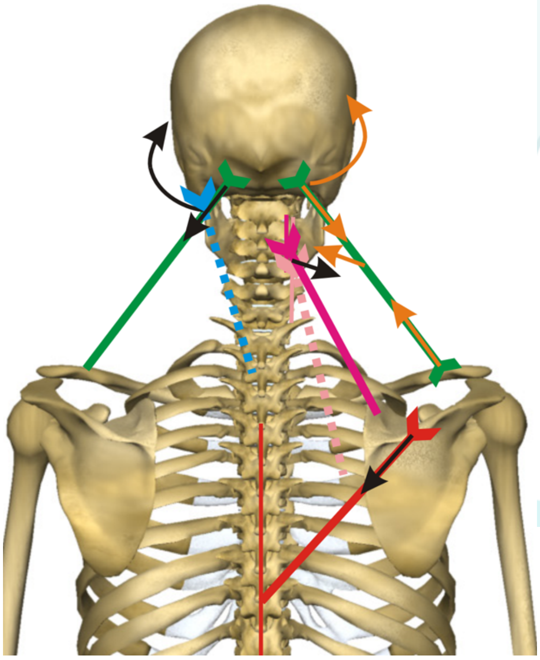


fig. 16: To balance all these resultants, other muscles must activate to fix the skeleton. In particular: to prevent lateral flexion and rotation of the cranium: contralateral upper trapezius fascicle; to prevent posterior flexion and rotation of the cranium: the sternocleidomastoids; to fix the shoulder girdle: the ipsilateral lower trapezius fascicle; to fix the cervical vertebrae, if the contralateral upper trapezius fascicle is insufficient: ipsilateral levator scapulae and scalenes. It goes without saying that this induces a chain activation of the entire muscular system in which each skeletal element will be fixed by other muscles.

11. Static vector muscle analysis: clinical applications

11.1 Methodological premises

This text considers alterations of physiological joint sequencing caused by muscular shortening.

Similar patterns may result from congenital or acquired conditions and specific pathologies; such cases are implicitly excluded here.

Analysis refers to intact, normally innervated muscles and absence of specific musculoskeletal pathology.

11.2 Deformity as expression of vector imbalance

Regardless of symptom type—pain, functional limitation, or both—an alteration of physiological joint sequencing is present and detectable.

Local vector analysis identifies the muscular forces primarily responsible.

Systemic implications are addressed in the non-linear analysis section.

12. The biomechanical role of muscles: movement and stability

Beyond movement, muscles contribute to joint stability and differ in fibre orientation and length.

Vectorially, longer muscles exert greater tensile force.

This explains why some muscles exert greater influence in determining deformities.

13. Physiological limits of muscle lengthening

In the absence of dislocations or specific pathology, no muscle can be anatomically "too long".

With joint misalignment, antagonist muscles are positioned relatively lengthened, yet remain within maximal physiological length.

These muscles increase tone to counterbalance deforming forces and are, in reality, shortened due to increased tone and connective adaptations.

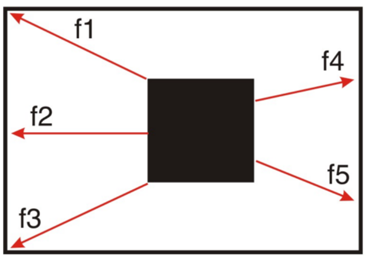


fig 1

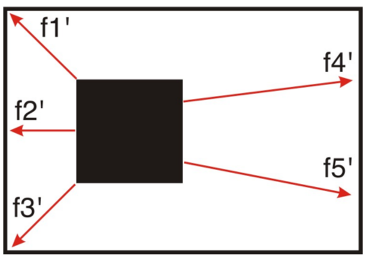


fig 2

fig. 17: The geometric model of dynamic equilibrium. In fig. 1, the black square is maintained in its position inside the outer square through the co-contraction of all acting forces from f1 to f5. The forces are not distributed symmetrically and if all increase the intensity of their traction force, the black square inside the white square (fig. 1), will move as in fig. 2. All forces from f1' to f5' are in excess tension: f1', f2' and f3' vectorially prevail and are shortened, f4' and f5' oppose the pulling force, increase their tone, but compared to the original position they are in lengthening. This lengthening, however, does not exceed the maximum lengthening capacity since the movement of the black square is within the limit given by the outer square.

To bring the black square back to the central position, it is not necessary to further increase the force expressed by f4' and f5', but to create conditions so that all forces from f1' to f5' (particularly f1', f2' and f3') decrease their intensity returning to the initial state from f1 to f5. Rebalancing is not achieved by strengthening muscles in a lengthened position but by reducing the excess tension of the dominant ones.

14. The importance of vector obliquity in biomechanics

Another key parameter is the obliquity of force application.

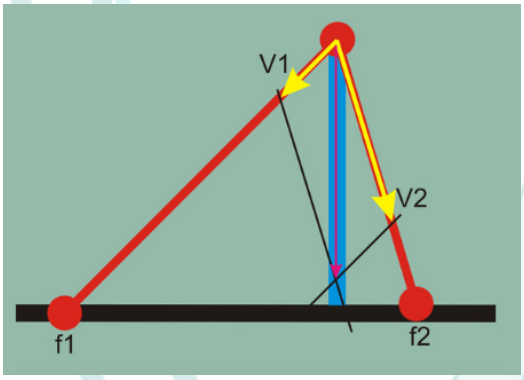


fig. 18: The non-rigid rod (in blue) is kept vertical by forces f1 and f2 expressed in vectors V1 and V2. Applying the parallelogram rule, it is evident that to balance the force of f1, f2 needs a vector of greater intensity.

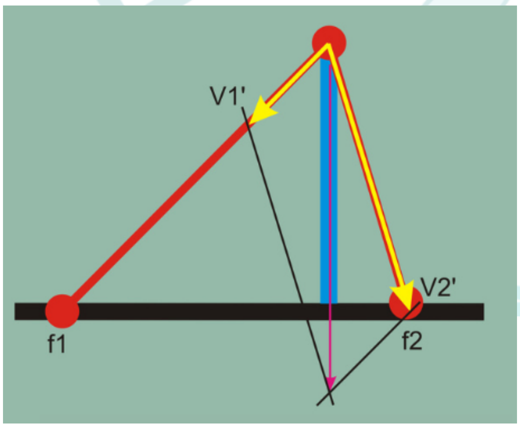


fig. 19: If f1 increases its traction force expressed with V1', f2 will in turn have to increase the traction force V2, reaching, in the graphic example, the limit of its balancing capacity.

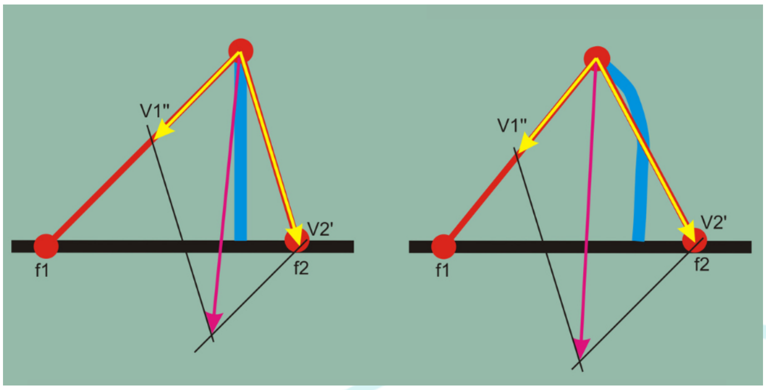


fig. 20: The further increase of the force of f1 expressed with vector V1", not being able to be balanced by vector V2', determines the bending of the rod

In the figure, the verticality of the rod is ensured by the balance of two diagonal forces which, having different angular functions, use asymmetric intensities.
The rod bends in the direction of the more oblique force, when the vector balancing capacity of the diagonal force having a smaller angular function is exceeded.
In the case where a diagonal force and a longitudinal force parallel to the rod act on the rod, the latter cannot balance the oblique force except by stiffening the rod itself in compression.

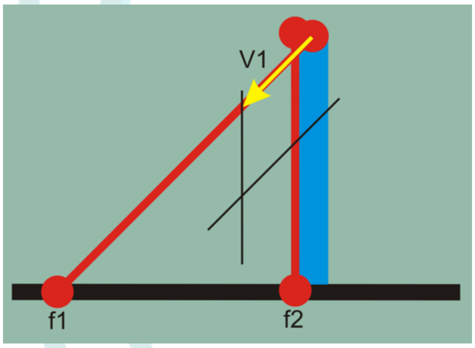


fig. 21: Applying the parallelogram rule, it is not possible to determine the intensity required by f2 to balance vector V1 expressed by f1 since, f2 having a vertical direction, the intersection of the parallels determines, at any point of application, a resultant that would bend the rod.

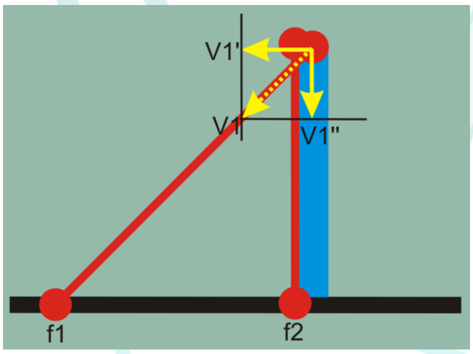


fig. 22: Decomposing vector V1, it is evident that it has a vertical component V1" that stabilizes the rod, and a horizontal component V1' that instead pulls it laterally.

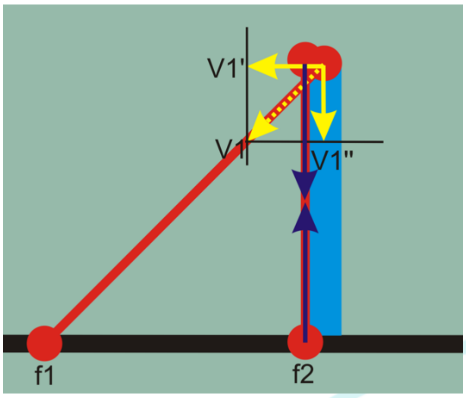


fig. 23: The horizontal component V1' cannot be vectorially balanced by vectors expressed by f2. In linear mathematics, a small force, in the absence of levers, cannot move a boulder due to its weight force. The only possibility for f2 to prevent the horizontal vector component of f1 is to express vectors of such intensity as to stiffen the rod.

15. Vector identification of deformity causes

For any joint misalignment, vector analysis aims to identify which force (muscle or muscle group) is favoured in producing the observed pattern.

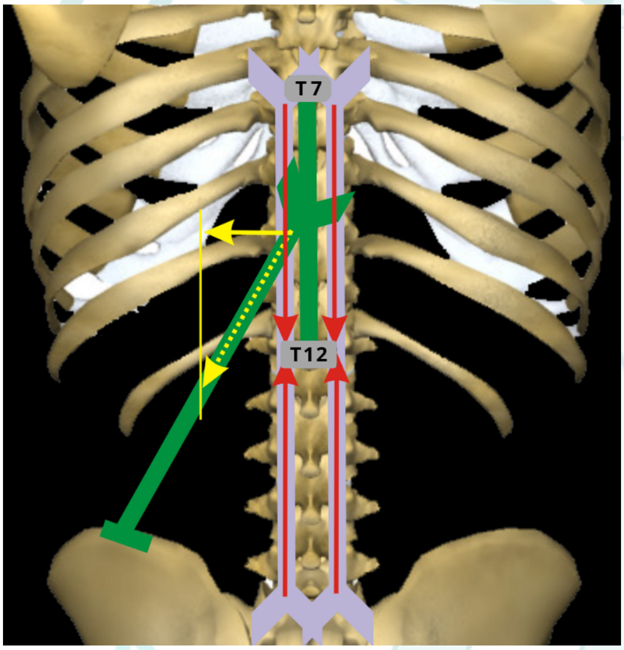


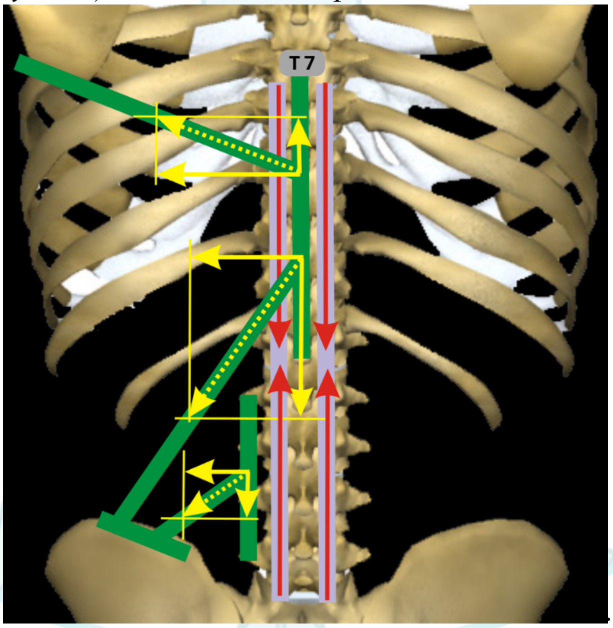
fig. 24: Considering the portion of the latissimus dorsi (green) from the iliac crest to the spinous processes from D7 to D12, the horizontal component of its vector (in yellow) cannot be balanced by vectors expressed by the paraspinals (purple). To prevent lateral deviation of the spine, the paraspinals express high-intensity vectors (in red) that block and stiffen the spine by compressing the intervertebral discs. A possible electromyographic investigation would show low activity of the latissimus dorsi (which however is the cause of the problem) and intense activity of the paraspinals (whose activity is however secondary and aimed at containing vertebral deviation).

The drawings have shown how increasing the vector intensity of an oblique force is potentially capable of creating greater skeletal displacement compared to a force having a longitudinal vector or one that is oblique but with a smaller angular function.
Furthermore, increasing the tension of an oblique vector forces longitudinal vectors to adapt by increasing their traction force, in an attempt to balance its effect by blocking the skeleton.

16. Vector asymmetries and muscular dominance

In almost all joints, muscular forces are vectorially asymmetric.
Dominant actions and subdominant actions are distinguished with respect to skeletal resultants.
In the scapulohumeral relationship, for example, the muscles that determine internal rotation of the humerus are dominant over those that determine external rotation, since the internal rotators are greater in number and endowed with longer and more oblique vectors.
The vector resultant of the internal rotators, if these express at high intensity, cannot be balanced by the vector resultant of the external rotators.
These anatomical vector dominances become particularly evident in neurological conditions such as spastic hemiparesis, where the loss of supraspinal inhibitory control allows intrinsic dominances to manifest fully.

fig. 25: The insertions of the latissimus dorsi on the iliac crest, scapula and humerus are considered fixed points. The vectors along the lines of force of the latissimus dorsi and quadratus lumborum (dashed yellow) have been decomposed into their horizontal and vertical components (yellow arrows)



. Containment of the horizontal components is achievable only through total stiffening of the spine by the action of the vertical vector components of the latissimus dorsi and the longitudinal vectors of the paraspinals (red arrows). More effectively, the horizontal components can be balanced by the horizontal vector components of the contralateral latissimus dorsi and quadratus lumborum (not shown in figure). Since the contralateral latissimus dorsi and quadratus lumborum also have vertical vector components, their activation combined with that of the paraspinals will achieve the goal of keeping the spine between D7 and L5 aligned but at the cost of its stiffening with consequent compression of the intervertebral discs.

It is rare to observe a hemiparetic patient with the humerus in spontaneous external rotation, precisely because the internal rotators are anatomically dominant.
Although the neurophysiological mechanisms of spasticity are different from physiological muscle shortenings, both conditions reveal the same anatomical reality: there are intrinsic vector asymmetries that, when not balanced by neural control or when altered by shortenings, determine predictable patterns of joint alteration.
This intrinsic asymmetry explains why certain alterations of the physiological articular sequence are more frequent than others.

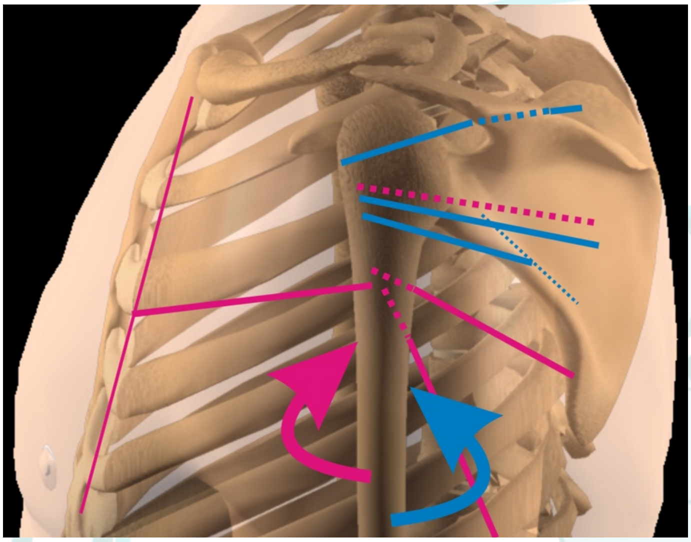


fig. 26: In purple the humeral internal rotators: latissimus dorsi, pectoralis major, subscapularis, teres major. In blue the humeral external rotators: supraspinatus, infraspinatus, teres minor. The dashed lines represent the course of non-visible muscles. From vector analysis of the muscles having significant rotatory component, a dominance in favor of the humeral internal rotators results due to number and length (vector intensity).

17. Revisiting the concept of “muscle weakness”

In vector logic, in the absence of peripheral neurological pathologies or other pathologies that interfere with muscle contraction, subdominant actions are not prevented by the "weakness" of the agonist muscles but by the excess tension of the antagonists.
Referring to the previous example, it is not the external rotators of the humerus that are in hypocontractile capacity, but the internal rotators in excess tension that impede the action.
As observed in the chapter on muscle mechanics, contraction, as a function of force/time, produces residual shortenings of connective tissue components that determine an increase in resistant force at the expense of work capacity.
In statics, what is perceived as "weakness" in maintaining position is actually the effect of excess tension of the dominant antagonists.
In dynamics, the shortening of both agonists and antagonists requires that both overcome their own internal resistant force before producing useful movement.
This determines less fluid movements, limited in range, or requiring compensatory strategies to be completed.

18. Active contraction versus residual shortening: two distinct phenomena

During active contraction, a muscle brings its insertions closer by temporarily reducing its total length.
Polyarticular muscles can reduce their length by up to 20% during maximal contraction, but express greatest mechanical efficiency when they shorten around 10%.
Monoarticular muscles can contract up to 50% but maintain best efficiency between 10% and 20%.
The biceps brachii, for example, with a 20% reduction of its total length achieves complete elbow flexion, but its maximum mechanical efficiency occurs at mid-movement, when the reduction is around 10%.
Quite different is the residual shortening of connective tissue components, which persists even after muscle relaxation.
Minimal percentages of shortening are sufficient to alter joint function.
A residual shortening of 1-2% can already limit joint range by 10-15 degrees.
Returning to the elbow example after immobilization: when the cast is removed, the typical 10-15° limitation in full extension corresponds to a residual shortening of the flexors of only 4-6 millimeters over a muscle length of 30 centimeters, or about 1.5-2%.
It is not the triceps that has become "weak," it is the flexors that have developed this minimal residual shortening of connective tissue components, sufficient, however, to prevent the last degrees of extension due to the increase in Resistant Force.
Shortening of connective tissue components should therefore not be imagined as a phenomenon of great magnitude: percentages of 1-2% are already sufficient to alter the physiological articular sequence and create clinically relevant functional limitations.

19. Functional specialisation of monoarticular muscles

Monoarticular muscles, when they develop contraction energy at maximum efficiency (about 10%), have limited capacity for movement of articular segments.
Their primary function is expressed in keeping the joint stable: they act as active ligaments capable of dynamically adapting to endoarticular stresses.

20. Methodological considerations for clinical application

The analytical treatment in the following chapters does not aim to be exhaustive but to provide interpretive tools adaptable to each individual case.
Not all potentially implicated muscles will be examined, but only those vectorially most significant.
In individual situations, it may happen that the most probable vectors prove negative: in that case, an analogous study procedure will be applied to the minor vectors.
In this second case, the rules of linear mathematics (proportionality between stimulus and effect) will no longer apply, but those of non-linear mathematics whereby even small signals are capable of producing significant changes.
The hierarchical approach guarantees diagnostic efficiency by focusing attention in the first instance on the most likely determining factors, and then deepening the analysis toward subtler but potentially decisive components, consistent with the principles of systemic complexity.

21. Chapter summary

Linear mathematics for district analysis. Proportional system where the increment of one variable corresponds to a proportional increment of another. Allows predicting the effect of muscular force on a specific skeletal structure.
Non-linear mathematics for systemic analysis. Small signals can produce large variations. Explains why slight muscle shortenings can generate significant and widespread symptomatology in the complex body system.
The vector and its three elements. Magnitude (intensity of muscular force), direction (line of force of the muscle), sense (from origin to insertion during contraction). Basis for biomechanical analysis.
The vector nature of muscular forces. Muscles exert traction forces on insertions through lines of force defined by the arrangement of their fibers.
Parallelogram rule. Tool for calculating the resultant of multiple muscular forces and identifying which muscles are responsible for a given dismorphism.
Anatomical vector dominances. Muscular forces are intrinsically asymmetric: there are dominant and subdominant actions. Example: humeral internal rotators are dominant in number and vector length compared to external rotators.
Movement limitation due to excess antagonist tension. In the absence of pathologies, subdominant actions are not impeded by "weakness" of agonists but by excess tension of antagonists that increase resistant force.
Vector obliquity determines effectiveness. An oblique force requires greater intensity to be balanced. Longitudinal muscles must stiffen the structure to oppose unbalanced oblique forces.
Monoarticular muscles as active ligaments. Maximum efficiency at 10% contraction, main function of dynamic joint stabilization rather than range of movement.
Residual shortening of connective tissue components. A shortening of 1-2% can significantly limit joint range. Shortening is a measurable mechanical condition that alters joint kinematics.

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