**INTRODUCTION**

Functional impairment of [parts of] the upper limb has many different expressions. Sound biomechanical analysis is at the basis of the management of the physical challenges involved. An outline of the basics of a mechanical systems approach is presented below.

Orthoses are among the many treatment options for upper limb impairments. An orthosis can be defined as a mechanical construction intended to improve a functioning part of the human body where the anatomical structures are still present. Orthoses fulfill their task by the exertion of forces onto the anatomical structures. Depending on the upper limb segments involved, and depending on the functional requirements [i.e. static support only, or dynamical assistance of muscle functions] a specific pattern of forces between the orthosis and the body is needed. Therefore, no universal upper limb orthosis exists. Each functional loss, in combination with personal wishes and demands, results in a different orthotic design. However, every orthosis needs to fulfill some basic requirements concerning cosmesis, comfort, and control\(^1\). Some examples of orthotic management of the upper limb are elucidated below.

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\(^1\) Some examples of orthotic management of the upper limb are elucidated below.
A system with three contact points. The system is at rest, i.e. $\sum \vec{F} = 0$, and $\sum \vec{M} = 0$. The direction and the magnitude of the force $F_1$ are known; only the direction of the force $F_2$ is known, and neither direction nor magnitude of the force $F_3$ are known, Figure 1a. In Figure 1b, the known lines of action are drawn, i.e. of the forces $F_1$ and $F_2$. They intersect at point $P$. This point is chosen as the moment point. As $\sum \vec{M} = 0$, the line of action of $F_3$ should also go through point $P$, Figure 1c.

With the lines of action of the forces $F_1$, $F_2$ and $F_3$ known, together with the known magnitude for force $F_1$, the magnitude of the other forces can be found from $\sum \vec{F} = 0$, i.e. by closing the triangle of forces, Figure 2. Starting out by drawing the force $F_1$, the line of action of force $F_2$ can be drawn starting at the head of the force $F_1$. Now, the line of action of force $F_3$ can be drawn. It should start at the head of force $F_2$, which is unfortunately not known. However, the head of force $F_3$ should be at the tail of force $F_1$. In the triangle created the magnitude of the forces is represented by the lengths of the sides of the triangle.

The magnitude of the individual force acting can be found from a graphical representation of the vector sum of these forces.
A system with only two contact points, Figure 3a, can be treated similarly. Here, the two forces must be equal in magnitude and have opposite directions in order to satisfy \( \Sigma F = 0 \). The two lines of action must coincide, otherwise \( \Sigma M \neq 0 \), Figure 3b.

Figure 3
A system with two contact points and one known force \( F_1 \), Figure 3a. For equilibrium the force in contact point 2 needs to have the same action line and the same magnitude as the force in contact point 1, Figure 3b.

With this graphical approach many [bio-] mechanical systems can be analyzed in a straightforward manner providing immediate understanding of the forces and moments acting upon the system. The two orthotic examples described below present additional illustration of [bio-] mechanical system analysis.

THE WILMER SHOULDER ORTHOSIS
The WILMER shoulder orthosis is designed for brachial plexus patients and patients with hemiplegia who suffer a complete paralysed arm. The basic functions of the orthosis are the neutralization of a shoulder subluxation and the suppression of oedema by horizontal positioning of the forearm. The biomechanics of this orthosis has been described extensively by Cool. Here, the description is limited to the main features of the orthosis. Because of cosmetics patients wish the orthosis could be worn underneath the clothing. That means neither the mitella nor the hemisling can be used. This is not regrettable, because both devices are unsuitable for the neutralization function. This can immediately be concluded out of the mechanics of the total orthotic system, Figure 4. Because the action line of the suspension force lies distally to the center of gravity of the bent arm no subluxation correcting force can exist.

Figure 4
The action line of the effective suspension force of a mitella or a hemisling lies distally to the center of gravity of the bent arm. Therefore, no subluxation correcting force can exist.
This conclusion paves the way to a proper structured orthosis. Displacement of the action line of the suspension force proximal to the center of gravity results in an attractive orthosis structure. The total system acts like a balanced arm, Figure 5. The weight of the forearm forces the upper arm upwards, thereby neutralizing a shoulder subluxation. One suspension point on the forearm is sufficient for the orthotic function described. This point is created by a tension band that suspends the arm on the shoulder. A shoulder cap transmits the suspension force to the body. A chest strap keeps the shoulder cap in place. All components are situated near the limb and therefore the orthosis can be worn underneath the clothing without problems.

Figure 5
Displacement of the action line of the suspension force proximal to the center of gravity results in an attractive orthosis structure. The total system acts like a balanced arm. The forearm and hand together force the upper arm upwards into the shoulder joint.

The WILMER orthosis, Figure 6, is the only device known that fulfils this task in reality.

Figure 6
The WILMER shoulder orthoses, designed to neutralize a shoulder subluxation, and to prevent forearm oedema.

Figure 7 presents the biomechanical analysis of the forces. Here, it should be noted that subluxation orthoses that use a humeral cuff to support the mass of the patient's arm are not capable of neutralizing the subluxation for a prolonged period of time. The humeral cuff supports the arm by friction forces on the skin only. Skin reacts to friction by creeping in a direction opposite to the friction force thereby trying to restore the normal skin position. As a consequence, the initial neutralizing action of the orthosis is lost.
Figure 7
Biomechanical analysis of the WILMER shoulder orthosis. In Figure 7a the forces acting on the sub-system of the forearm are shown. The force in the elbow returns in Figure 7b, where the forces acting on the sub-system of the upper arm are shown. For equilibrium a reaction force in the shoulder is needed. In Figure 7c, the subsystems of forearm and upper arm are combined to the system of the complete arm. The force in the elbow is now an internal force of the system. The resulting gravity force of the complete arm acts distally of the suspension force. The reaction force in the shoulder, the same as in Figure 7b, ensures the equilibrium of forces and indicates the successful neutralization of the subluxation.
The WILMER shoulder orthosis comprises the following advantages:

- effective neutralization of a shoulder subluxation
- suppression of oedema
- reduced pain
- reduced arm sway, therewith reducing the risk of possible injuries
- allows passive exo/endo rotation of the humerus
- light weight; the total mass of the orthosis is 200 g.
- comfortable to wear
- easy donning and doffing
- invisible to wear, underneath the clothing; which gives a cosmetic appearance

The WILMER Adjustable Shoulder Orthosis
With the WILMER shoulder orthosis, clothing activities are sometimes found to be hampered by the orthosis because of the 90° flexed arm position. In order to facilitate donning and doffing of clothes, an adjustable version of the orthosis has been developed. By pushing against a knob that is located near the elbow in the suspension strap an unlocking action is performed. The arm with the orthosis can now be extended. Bringing the arm back in the 90° flexed position engages the lock again, enabling the orthosis to function. The working principle and the fitting procedure of this adjustable shoulder orthosis is exactly the same as for the standard version.

THE WILMER ELBOW ORTHOSIS
The WILMER elbow orthosis is a dynamic orthosis designed for patients with a paralysed elbow due to a brachial plexus injury or due to hemiplegia. A paralysed elbow can be brought into flexion by shoulder abduction angles over 90°. However, abduction angles that large are not acceptable both functionally and cosmetically. By adding an orthosis to the paralysed arm a decreased abduction angle necessary for full elbow flexion results, Figure 8. The top part of this figure indicates a simplified block diagram for the system paralysed elbow. The graph shows the switch to full elbow flexion at abduction angles over 90°. In the lower part of Figure 8 an orthosis is added. The orthosis offers a positive feedback as indicated in the block diagram where the orthosis output is added to the input abduction. This results in a decreased abduction angle necessary for full flexion. In practice the feedback is adjusted so that an abduction angle of approximately 30° initiates elbow flexion. Smaller abduction angles do not result in elbow flexion.

Figure 8
System analysis of a paralysed elbow. The top part of this figure indicates a simplified block diagram for the system paralysed elbow. The graph shows the switch to full elbow flexion at abduction angles over 90°. In the lower part of Figure 8 an orthosis is added. The orthosis offers a positive feedback as indicated in the block diagram where the orthosis output is added to the input abduction. This results in a decreased abduction angle necessary for full flexion.
The WILMER elbow orthosis, Figure 9, is a unilaterally construction with two hinged frame bars made from stainless steel tubing. It’s very simple operating principle in understood quickly by patients. A new patient controls the orthosis correctly within a few minutes. Shortly thereafter he or she discovers dynamic control. The orthotic forearm can be positioned by an anteflexion pulse also. Patients master a quick hardly observable abduction/anteflexion upper arm control movement within the first hour of orthosis receipt. This quick learning process eliminates the clinical exercises non-appreciated by patients.

![Figure 9](image)

*Figure 9*

The WILMER elbow orthosis. The inset shows the forces on the four fittings during normal operation. As these forces act within one plane, parallel to the plane defined by the forearm frame bar and the upper arm frame bar, the unilateral hinge is free from torsional moments.

The orthosis is fitted to the patient’s arm by two fittings on either side of the elbow joint. This way the orthosis only loads the skin with normal forces, not with shear forces. The fittings themselves are made from perforated plastic sheet material. In this way perspiration is not hampered. The fittings are supported only in their centre so they can automatically adapt themselves to the shape of the arm of the patient.

The body adaptive fittings are mounted in a frame. In orthopaedic practice two sided hinged frames are usual. Two sided hinges only work well when carefully aligned, symmetrically loaded and mounted to a rigid frame. In practice, these requirements are not fulfilled. Usually, the original poor alignment is worsened by a one sided locking mechanism. The two-sided hinges used in practice introduce high friction forces, leading to malfunction, noisy operation, wearing parts and a small time between failures.

A force analysis of elbow orthoses shows a one sided hinge to be free from torsion moment during normal operation. Also in the locked position a one sided hinged orthosis is only loaded in the rotation plane of the hinge. Moreover, one-sided hinged orthoses benefit cosmetics by its unilateral construction, Figure 10, and favours the comfort of wearing by reduced weight and easy donning and doffing.

The orthosis is constructed out of stainless steel tubing. The unilateral frame bars are cold deformed oval for increased stiffness. In the compilation phase the fitting carriers can slide along the frame enabling their correct position to be determined experimentally. In the correct position found the fitting carriers are fixed to the frame. This time saving fitting procedure benefits costs.
A locking mechanism is added to the orthosis to enable the patient to retain the flail arm in the flexed position independent of the abduction/anteflexion angle. In this locked position the arm + orthosis is suitable to lift and carry objects. A second locking position at the near-extended arm enables pushing or clamping of objects. Moreover, this locked position is very useful donning and doffing the orthosis. The locking mechanism operates automatically and is controlled by the patient with his or her handicapped side. In Figure 11 the operation cycle is illustrated.

The patient can flex and extend the elbow over the whole range of motion - from A to D - without interference of the locking mechanism. Only if he switches from flexion to extension in the small angle area indicated with C the locking mechanism will engage and lock the arm against extension in an approximate 90° flexed position. To unlock the arm the patient has to flex the arm into area D. The lock in the near-extended position is engaged by a switch from extension to flexion in the small angle area indicated with B. An extension into area A unlocks the mechanism.
This locking mechanism can restrain some activities, like driving a car. Therefore, to prevent unexpected locking of the orthosis, the locking mechanism can be switched off by pulling a knob located at the wrist-region. A second pull engages the locking mechanism again.

The WILMER elbow orthosis comprises the following advantages:

- restores some elbow function
- comfortable to wear because of body adaptive perforated fitting areas
- light weight. A complete elbow orthosis weighs approximately 150 g.
- invisible to wear underneath the clothing at the medial side of the arm
- cosmetic appearance
- easy donning and doffing
- quick straightforward fitting procedure
- automatic locking mechanism

**The WILMER Elbow Orthosis For Children**

For the youngest children with a partial or complete paralysis of an arm the WILMER elbow orthosis as described above is not suitable. The hinge and locking mechanism are too voluminous to be fitted on these children. In our experience the lower border is approximately 4 years of age. For children up to this age a separate elbow orthosis has been developed based on the same operating principle. The orthosis, again, consists of two hinged bars with a spring attached in between them. Four fittings transfer the forces between the orthosis and the arm vice versa, similar to the WILMER elbow orthosis. No locking mechanism is incorporated. The weight of the orthosis depends to a large extend on the age of the child. It varies from 35 gram for a one-year-old child to 80 gram for a child of four years of age.

With this WILMER elbow orthosis for children the child can actively flex his or her arm again. It is possible to perform bimanual tasks in the whole range of motion of the arms. Therewith the possibilities to play and the development of the child are enhanced.

The fitting procedure is quite similar to the WILMER elbow orthosis. At least every six months the fitting and the spring need to be adjusted because of growth of the child.

**The WILMER Elbow Extension Orthosis**

Sometimes it is desired to assist the arm to extend. Various medical indications can be the basis of this desire, muscle spasm being the most frequent one. Based on the experience with the WILMER elbow flexion orthosis, an elbow extension orthosis has been developed.

The orthosis consists of two hinged bars, fixed on the arm with four perforated, body adaptive fittings. An adjustable spring mechanism extends the orthosis. Some active function can be achieved. By relaxing the muscles flexing the elbow, the orthosis will extend the arm.

**CONCLUDING REMARKS**

A graphical approach to the analysis of [bio-]mechanical systems provides a quick and thorough understanding of the magnitudes and directions of forces and moments acting upon the system. Basic biomechanical principles and a sound system analysis providing a firm understanding of the inevitable force patterns, have resulted in the design of attractive and effective orthoses for the upper limb. The WILMER shoulder orthoses is the only orthosis known that neutralizes a shoulder subluxation. The WILMER elbow orthosis enables someone with a flail arm to actively flex and extend the elbow again, whereas the locking mechanism of the orthosis offers several functional advantages for the wearer.

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