

Biomechanics of orthoses for the subluxed shoulder

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Abstract

Based on biomechanics several operational principles for the neutralization of a shoulder subluxation are described. The pros and cons of the operational principles are discussed. A detailed analysis of the forces acting on the upper and lower arm indicates a preference for only one of the operational principles and explains why the arm sling and hemisling fail in the elimination of subluxation. With the operational principle selected a shoulder orthosis has been developed. Clinical results are given.

Introduction

As a consequence of a brachial plexus lesion or a hemiplegia a subluxation of the shoulder frequently occurs. Smith and Okamoto (1981) have described several designs of orthoses for the subluxed shoulder, together with a checklist for hemiplegic slings. However, the orthoses described are difficult to evaluate because no operational principles are provided. Furthermore the checklist contains no information to evaluate control functions.

Often a new orthosis is described by the moulding techniques applied and the materials used. This is valuable, but cannot replace an indication of the operational principle. It must be doubted whether all the prescribed orthoses give the results expected.

The proper functioning of an orthosis requires that the laws of biomechanics are obeyed. In a well designed anti-luxation shoulder orthosis the correct forces must be exerted at the right action point. Otherwise the luxation is either uncorrected or only partially corrected.

Biomechanics

The theory of biomechanics comprises the mechanical laws of movement and equilibrium of forces, together with the visco-elastic behaviour of biomaterials.

In the case of a shoulder orthosis for the neutralization of subluxation it is sufficient to consider only static forces acting on the paralysed arm.

The analysis is simplified to the two dimensional situation. Only the forces and movements acting in the plane through the upper and lower arm are considered. It is assumed that this is a vertical plane containing the gravity forces. The contact forces between arm and trunk are omitted.

For a comfortable orthosis the contact forces between the orthosis and the skin of the arm need careful control, both in direction and magnitude. The direction of these contact forces must be perpendicular to the skin surface. Components of the contact force in line with the skin surface give rise to excessive skin displacements, and have a bad effect on the correct operation of the orthosis. The resulting friction forces on the skin are intolerable unless very small and intermittent. The reaction of the skin to friction is to creep in a direction opposite to the external friction force thereby trying to restore normal skin position. This has an adverse effect on the function of the orthosis.

Experience has shown that skin pressures up to 0.5 N/cm² are tolerable even on atrophied skin. The orthosis developed as a result of these studies is designed in accordance with this value. The occurrence of skin friction is prevented.

Operational principles

The neutralization of a subluxation requires that the paralysed arm is elevated. After that

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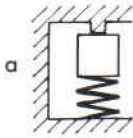
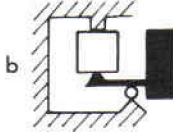
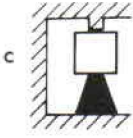
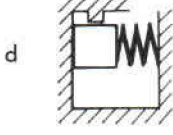
	Description	Advantages	Disadvantages
	Elevation force applied by spring	Controlled subluxation	Variable shoulder force
	Elevation force applied by counterweight	Controlled subluxation constant shoulder force	Heavy and voluminous because of counterweight
	Elevation held by clamping	Insensitive to disturbing (dynamic) forces	Sensitive to movements of fixation point
	Elevation held by friction		Sensitive to disturbing forces High normal forces

Fig. 1. Different operational principles for the elevation of a mass. The mass is indicated by a white square. The elevation force application is shown black.

the arm must be held in the elevated position. This means that a force equal to the weight of the arm and acting upwards, must be continually present. For the generation of that force different solutions exist. Each solution represents an operational principle.

In Figure 1 different operational principles for the elevation of a mass m are indicated. The mass m can be elevated by the action of a spring (a) or a counterweight (b). In the elevated position no clamping is necessary. The restoring force caused by spring or counterweight is always present and corrects immediately any deviation from the elevated position.

Once the mass is elevated by some external force, it can be held in the elevated position by the action of a clamp (c) or by friction (d). These operational principles are less favourable than (a) or (b), because no restoring force is present. The influence of a disturbing force or movement is not controlled. Displacement of the fixation point of the clamp (c) or overcoming of the friction force (d) reintroduces subluxation. Application of the operational

principles (c) or (d) cannot guarantee that subluxation is neutralized.

Each working principle has its own advantages and disadvantages. These are indicated in Figure 1. On disturbance the spring of principle (a) causes a variable pressure force. Principle (b) has a favourable constant pressure force, but the counterweight necessary is voluminous and heavy. As discussed the principles (c) and (d) are very sensitive to disturbing movements and forces. Principle (d) depends on friction forces, which always require very high normal forces. Many different designs can be developed to apply these principles.

Forces on the upper arm

To neutralize a subluxation the humerus must be elevated until in the gleno-humeral joint small or zero play is left. The upper arm has a weight W_u . For the elevation of the upper arm a vertical force F_u which exceeds the weight W_u must be applied. An upward force F_u that exceeds W_u results in a shoulder force.

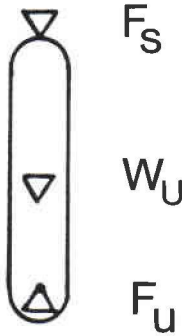


Fig. 2. Forces acting on the upper arm. The equilibrium condition is $F_s + W_u = F_u$. For a small force F_s the force F_u only slightly exceeds W_u .

F_s between humerus and scapula (Fig. 2). Any positive value of F_s will ensure the subluxation is neutralized. The value of F_s is not critical, but preferably should be small. High forces between humerus and scapula should be avoided. As an indication F_s should never exceed W_u . With that value the upward force $F_u = 2 W_u$.

With preference the upper arm rests in the vertical or nearly vertical position. This position is both comfortable and cosmetically acceptable. Hence the force F_u has to be axially exerted on the vertical upper arm. As it is undesirable for F_u to act on the outer area of the upper arm it has to act on the upper arm internally. The elbow joint is the only applicable point for the force F_u to act on the humerus.

In the elbow joint the vertical force F_u can act on the humerus without risk of damage to the joint. A sound elbow joint can transmit high magnitude forces in the extended as well as in the flexed mode.

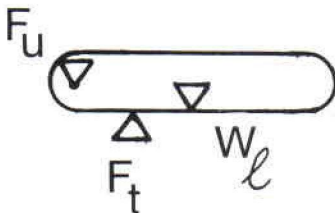


Fig. 3. Forces acting on the lower arm. The equilibrium condition is $F_u + W_l = F_t$. Considering also the equilibrium condition of the upper arm gives $F_t = F_s + W_u + W_l$. The minimum value for F_t is the weight force of the whole arm.

Forces on the lower arm

In the elbow joint a force F_u acts upwards on the humerus. This results in a downward reaction force F_u on the lower arm. The lower arm has weight W_l acting through its centre of gravity. For equilibrium of the lower arm at least a third force F_t is necessary. Both forces F_u and W_l act vertically downward; therefore F_t has to act vertically upward.

According to the laws of mechanics the action point of the force F_t is nearest to the biggest downwards force. In practical situations F_u roughly equals W_l . That means the action point of F_t is roughly centred between the elbow and the centre of gravity.

The lower arm is approximately cylindrical. As no friction forces are tolerable the lower arm has to be positioned perpendicular to the force F_t . Thus, the vertical force F_t requires a horizontally positioned lower arm.

In Fig. 3 the lower arm is shown schematically with the forces acting on it. Other force systems could also satisfy equilibrium conditions.

The lower arm as counterweight

In the preceding paragraphs the forces acting on the upper and lower arm are defined. Combination of Figures 2 and 3 produces Figure 4. F_u is an internal force and is therefore not indicated in Figure 4.

If the action point of force F_t is considered fixed the force system can be represented as shown in Figure 4. This figure resembles the counterweight system of Figure 1b. The weight of the lower arm elevates the upper arm. Thus the lower arm acts as the counterweight. With no additional counterweight necessary the disadvantage of this operational principle (heavy, voluminous) disappears.

In this circumstance the operational principle 1b is highly favourable because of:

- Controlled subluxation by the continuously present elevation force. No need for clamping of the arm.
- Small constant shoulder force only slightly influenced by dynamics.
- The lower arm acts as a counterweight. No additional masses required.

Illustration of the operational principle

In principle, neutralization of subluxation is obtained by the addition of a fixed point to the

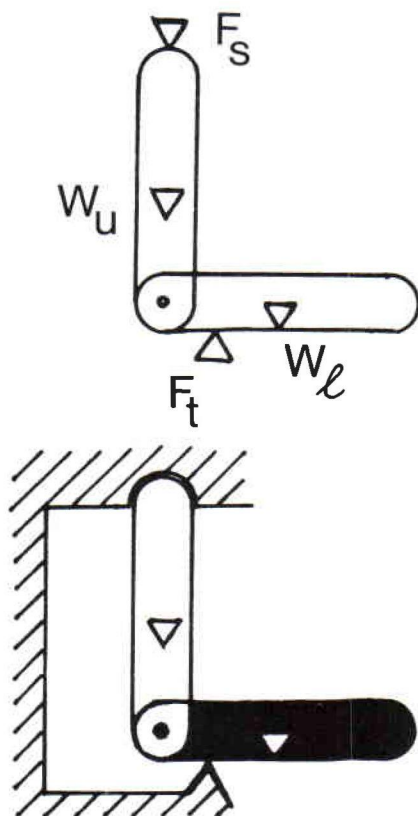


Fig. 4. Combining Figures 2 and 3 gives Figure 4, top. The resultant force F_t delivered by a fixed support produces Figure 4, bottom. The lower arm is shown black resembling Figure 1b. The lower arm acting as a counterweight removes the disadvantage of operational principle 1b.

paralysed arm. However the position of that fixed point is of particular importance. The different possibilities are illustrated in Figure 5.

In Figure 5 the paralysed arm is represented by two pivoted bars. One bar represents the upper arm, the other bar represents the lower arm. In the centre of gravity of each bar the weight force acting is indicated by a white triangle. The pivot represents the elbow joint, which is indicated by a small circle in the figure. A black triangle indicates the position of the fixed point. It must be remembered that the fixed point represents the suspension point of the arm. It is fixed relative to the body, not to the environment.

The different possibilities displayed in Figure 5 are described below

5a — The paralysed arm is hanging down from

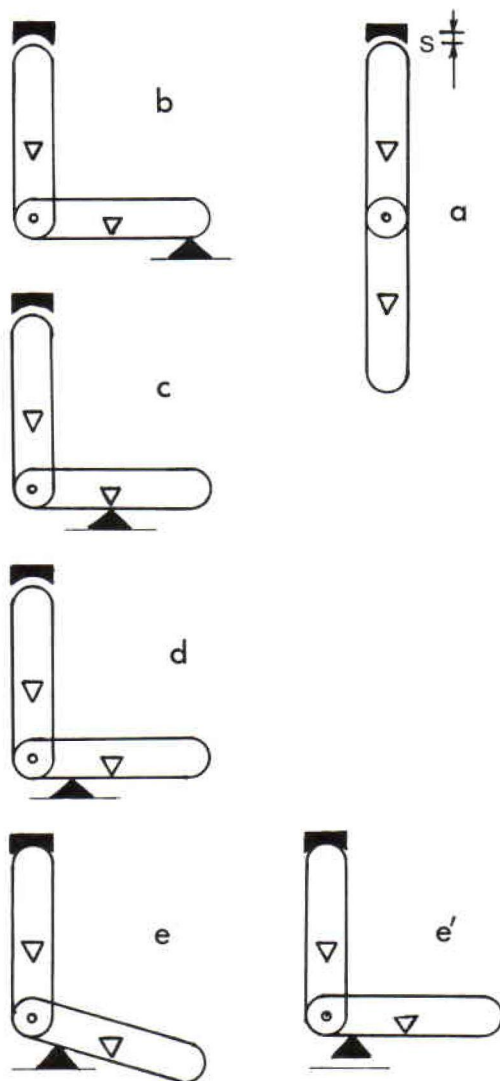


Fig. 5. The paralysed arm with acting forces (see text).

the shoulder. A subluxation s exists, caused by the weight forces W_u and W_l of the upper and lower arm respectively.

5b — The arm is suspended at the distal end of the lower arm. The weight of the lower arm is only partly supported. The subluxation s still exists.

5c — The lower arm is suspended just at the centre of gravity. The weight of the lower arm is counteracted. The subluxation is caused by the weight of the upper arm only.

5d — The fixed point of the lower arm is centred between the two centres of gravity.

Exact balance of both the upper and the lower arm is obtained. Although no subluxation force exists, the subluxation is still present.

5e — The exact balance of 5d is disturbed by positioning the fixed point a small distance nearer to the elbow joint. Now the lower arm weight forces the upper arm upwards, thereby eliminating the subluxation.

5e' — The position on the lower arm of the fixed support point is decisive to neutralize subluxation. In 5e the lower arm inclines due to the displacement s of the elbow joint. The horizontal position of the lower arm can be restored by a small elevation of the fixed point.

Suspension

In static systems one single force never operates. Forces always are generated in pairs. The action of a force necessitates opposite force action elsewhere. A spring can deliver force only if the other end of the spring can react against a fixed point. The same is true for a rope, a rod and any arbitrary construction. The two forces always have the same action line.

The force F_t needs a reaction force to form a pair. Therefore two possibilities exist: the paralysed arm can be suspended from the shoulder or the hip can support the arm. In the

situation of Fig. 6 (left) a tension band suspends the arm on the shoulder. A shoulder cap transmits the suspension force to the body. In the situation of Fig. 6 (right) a compressive rod supports the arm. A band around the hip transmits the supporting force to the body. In both situations the force pairs to the body have corresponding magnitudes and the same directions.

External suspension of the arm weight from the shoulder localizes all body forces to the arm and shoulder, imitating the normal situation. This suspension system has been chosen for the orthosis developed. Support of the arm weight by the hip introduces eccentric forces to the body, but leaves the shoulder region unloaded. In some practical situations this solution can be advantageous.

Why arm sling and hemisling fail

With knowledge of the possible operational principles it is easy to understand why many solutions suggested in the literature do not give the results expected. This is illustrated below by an analysis of the hemisling and the arm sling.

A hemisling is a simple band resting on the sound shoulder; one end is looped around the paralysed lower arm near the elbow, the other end is looped around the hand on the injured side. Figure 7 shows schematically the arrangement with the two forces F_e and F_h acting on the lower arm near the elbow and the hand respectively. A subluxation could be neutralized if the resultant force of F_e and F_h acted in accordance with Figure 5e. Then F_e is required to be of much greater magnitude than F_h . However that is unachievable. Any difference between the two forces is caused by friction between band and skin at the shoulder. As previously discussed the skin does not accept friction over long periods. Therefore in the schematic drawing of the hemisling, rollers are introduced, equalizing the forces F_e and F_h . The resultant force is centred between them, near the middle of the lower arm. The force acting at that point is unable to neutralize subluxation. The situation is similar to figure 5c.

The same is true for an arm sling. The only difference from the hemisling is the distributed pressure along the lower arm. These pressures unite in two forces around the neck of the patient. Because the skin of the neck does also

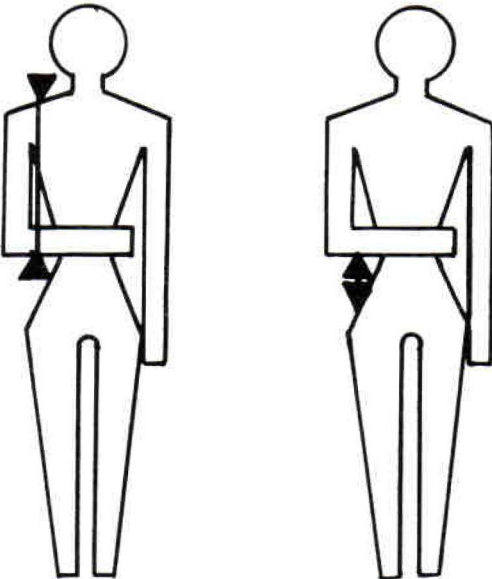


Fig. 6. By suspension of the arm the suspension force F_t combines with a reaction force on the shoulder (left) or on the hip (right)

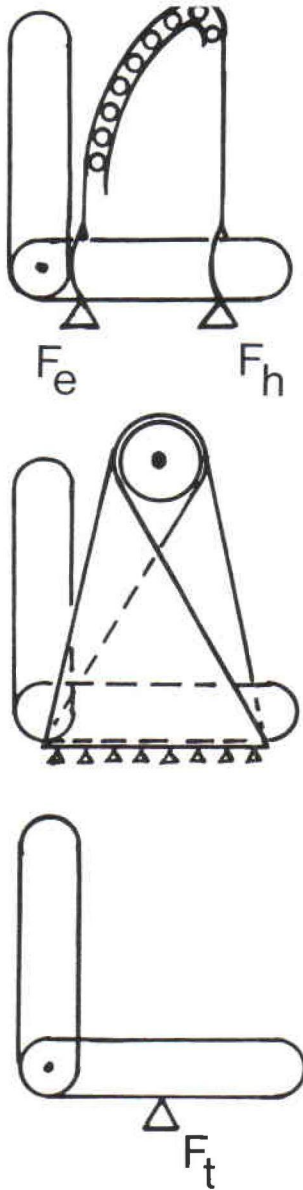


Fig. 7. The hemisling (top) as well as the arm sling (centre) give rise to midarm suspension forces F_t (bottom). In accordance with theory subluxation is not neutralized.

not accept friction these forces have equal magnitude, leaving a uniform pressure distribution on the lower arm with a midarm resultant. Therefore also the arm sling cannot neutralize subluxation of the shoulder.

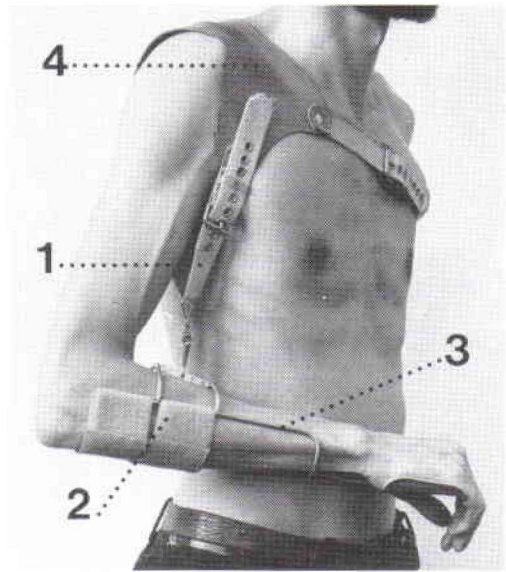


Fig. 8. Patient with orthosis, 1-textile tension band; 2-leather suspension strip; 3-stainless steel brace; 4-textile or leather shoulder cap.

The correct orthosis

The orthosis designed clearly demonstrates the operation principle selected. (Fig. 8). The tension band 1 suspends the paralysed arm at the shoulder. The shoulder cap 4 transmits the suspension force F_t to the body. At the other end the suspension force is transmitted to the lower arm by the brace 3. The brace 3 is constructed for various reasons.

- The suspension force F_t has the magnitude of the weight of the arm. To transmit this force to the skin the surface area is calculated using the maximum allowable pressure 0.5N/cm^2 . The result is a required area roughly 50 cm^2 . For reasons of comfort a strip of leather provides the contact. The strip dimensions are 5 by 10 cm^2 . For a good pressure distribution to the small suspension band 1 the leather strip 2 ends in the metal parts of the brace.
- The leather strip 2 is mounted between two separated metal bars.
- In many practical situations the wrist is also paralysed and needs support. Of course a separate cock-up brace for the wrist could be used. For reasons of simplicity the cock-up brace is integrated in the orthosis.
- The integrated construction gives the possibility of positioning the leather strip

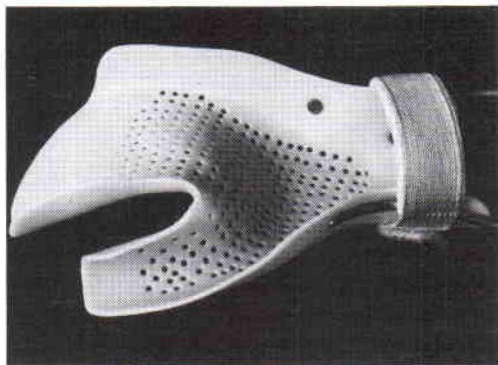


Fig. 9. Spasm suppressing hand support for hemiplegic patient.

relative to the hand. This eases donning and doffing of the orthosis.

The cock-up part of the brace provides a hand support. Depending on the planned use of the orthosis completely different supports have been designed. Patients with a brachialis lesion often prefer a very small self-adaptive hand support. For patients with hemiplegia a spasm suppressing hand support can be made (Cool et al., 1984). Figure 9 shows a photograph of such a hand support.

The metal parts of the orthosis are constructed of stainless steel. This material offers some advantages.

- Very high strength/weight ratio. This gives the possibility of constructing extremely lightweight braces.
- High corrosion resistance. For orthopaedic applications stainless steel is one of the best materials available.
- Fairly machinable and weldable.
- Commercially available in a variety of profiles and many dimensions.

With the designed orthosis an accurate analysis of all forces acting can be made. The result is similar to the analysis above; however some forces deviate from the exact vertical direction. As a result the lower arm is preferably suspended in a slightly inclined position, perpendicular to the suspension-band.

Concluding remarks

Basic biomechanical principles and control qualifications lead to the design of an orthosis for the neutralization of shoulder subluxation. From an understanding of the inevitable force patterns the designed orthosis is the logical development.

Many patients favour the new orthosis because of:

- reduced pain
- light weight (total weight 150 g).
- easy donning and doffing
- comfortable wearing
- reduced arm sway
- invisible to wear (underneath clothing)

At the moment the orthoses are distributed in The Netherlands, Belgium and West Germany by Basko Camp B.V.; Postbox 8359, 1005 AJ Amsterdam. In the last years over 1600 orthoses were supplied.

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