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

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.

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
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 the shoulder. A subluxation s exists, caused by the weight forces Wu and Wl 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.

Fig. 4. Combining Figures 2 and 3 gives Figure 4, top. The resultant force Ft 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.

Fig. 5. The paralysed arm with acting forces (see text).
Exact balance of both the upper and the lower arm is obtained. Although no subluxation force exists, the subluxation s 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 Ft 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 Fe and Fh acting on the lower arm near the elbow and the hand respectively. A subluxation could be neutralized if the resultant force of Fe and Fh acted in accordance with Figure 5e. Then Fe is required to be of much greater magnitude than Fh. 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 Fe and Fh. 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
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.

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 $0.5\text{N/cm}^2$. The result is a required area roughly $50\text{cm}^2$. For reasons of comfort a strip of leather provides the contact. The strip dimensions are $5$ by $10\text{cm}^2$. 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. 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.

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

REFERENCES
