

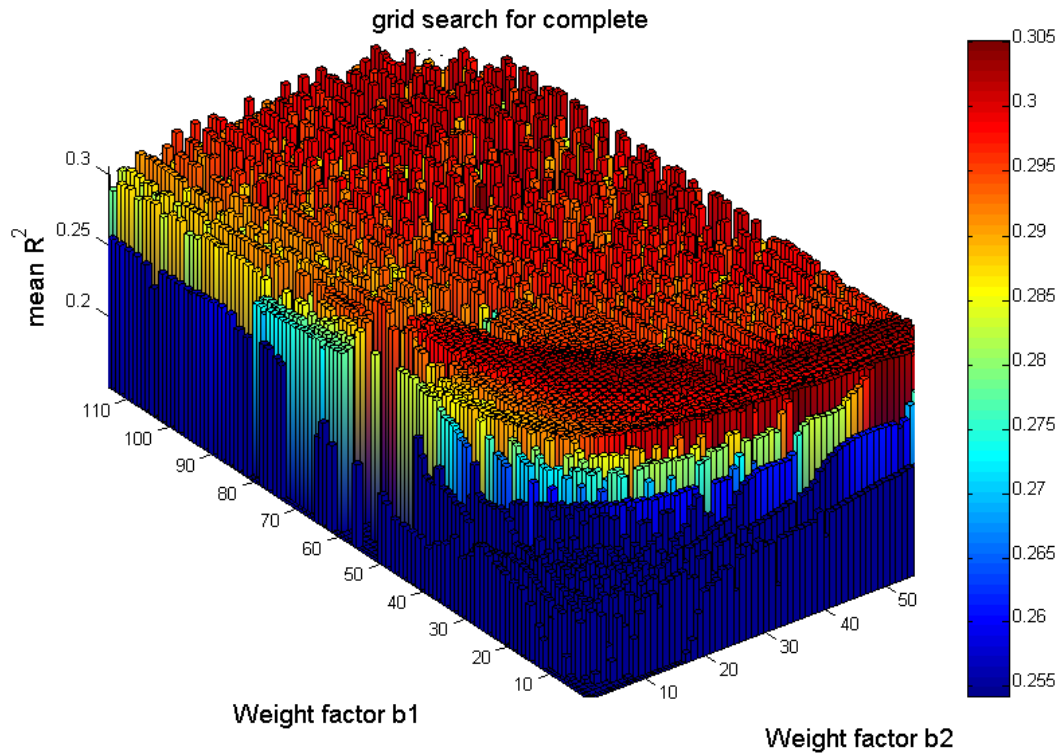
## **Appendix A**

### *The grid search*

The outcome of the grid search for the complete data set is the overall explained variance of all the participating flexor and extensor muscles classified in particular tasks (Figure A - 1). The 3D bar chart shows the weight factors plotted on the x and y axis respectively and the height of the bar chart corresponds to the overall  $R^2$ . The overall explained variance varies between the 0.1 for the least optimised cost function to 0.31 for the optimal weight factors. A clear rise is visible of the overall variance up until a range of combinations for weight factors. Increasing either of the weight factors beyond this range deteriorates the cost function slightly. The maximal overall explained variance is obtained at the cost function with weight factors  $b_1 = 3$  and  $b_2 = 50$  and results in a value of 0.31.

This appendix tries to elaborate on the contribution of the overall effect of measurements done at different angles as well as an extra classification of the extensor and flexor muscles under the particular angles. This might give insight of the importance of different factors for a measurement protocol needed for a more distinct optimisation of the weight factors of the energy-related cost function for the Delft Shoulder & Elbow Model (DSEM).

Furthermore, grid search bar charts are given for each of the muscles used to obtain the overall explained variance. This specification will show an overview of which muscles show good linearity with the predicted outcome of the various energy-related cost functions integrated in the DSEM and which muscles do not show linearity.



**Figure A - 1: Outcome of the grid search. Weight factors b1 and b2 are varied and the height of the bar corresponds to the mean explained variance over all of the muscles.**

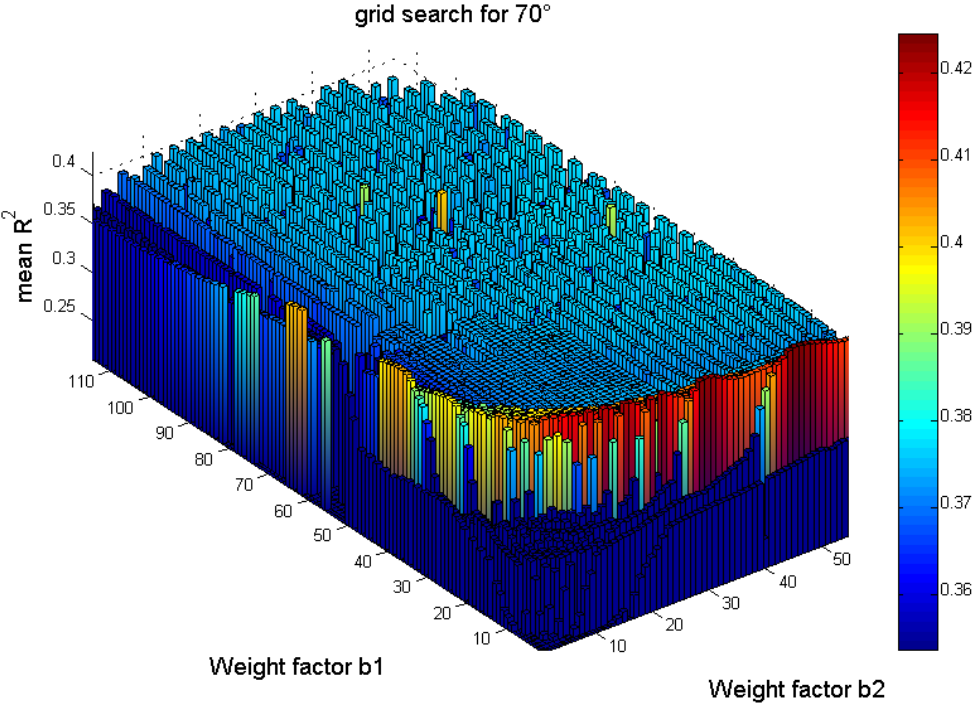
### **The effect of angles**

Dividing the overall outcome in the contributions of each of the angles shows that increasing the flexion angle decreases the overall explained variance. Since the analysis method over all the measured flexion angles is the same one has to look at how the analysis is constructed to get an indication in what factors play a role that can explain the differences of the explained variance. The explained variance gives an indication how well the measured activity of the muscles is linearly related to the corresponding force output of the DSEM. Thus, these results indicate that while increasing the flexion angle the linear relation between the two measures decrease.

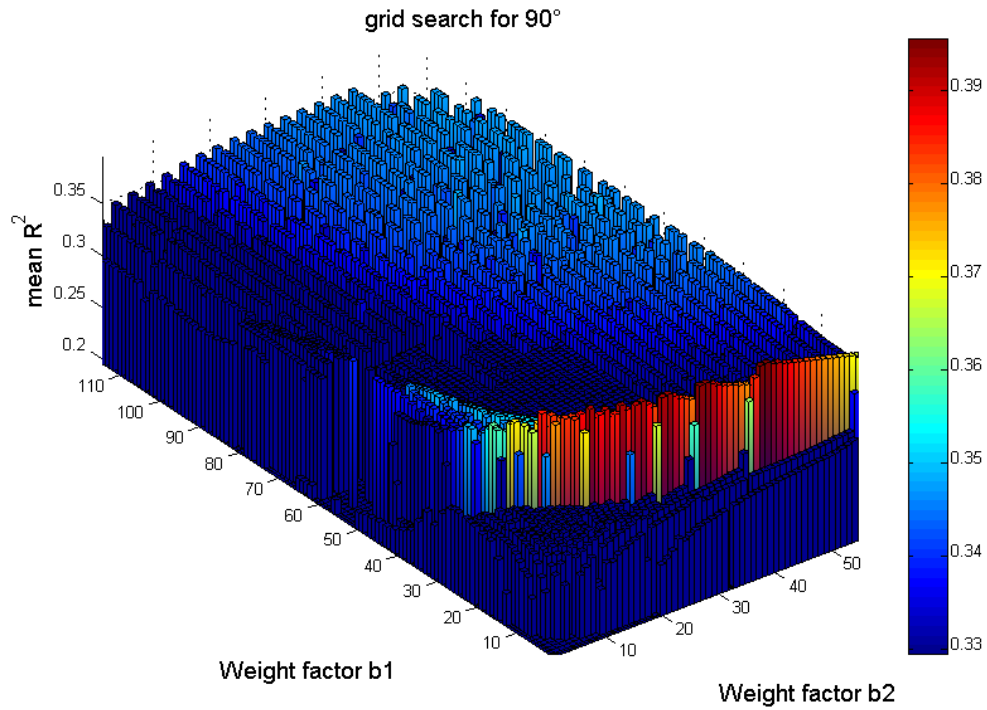
This may be due to one of the drawbacks of measuring muscle activity by means of electromyography (EMG). One of the most important sources of error in interpreting surface EMG is what is known as crosstalk. It is defined as a contamination of the EMG signal by nearby muscle's activity. It is known that the amount of crosstalk depends on the thickness of the subcutaneous layer, the

detection system and non-propagating signal components (Hug 2010). Crosstalk factors vary among test subjects and different poses the arm assumes at which the muscles are measured. Therefore, it is plausible that the muscle activity measured when the humerus is in retro flexion is less accurate.

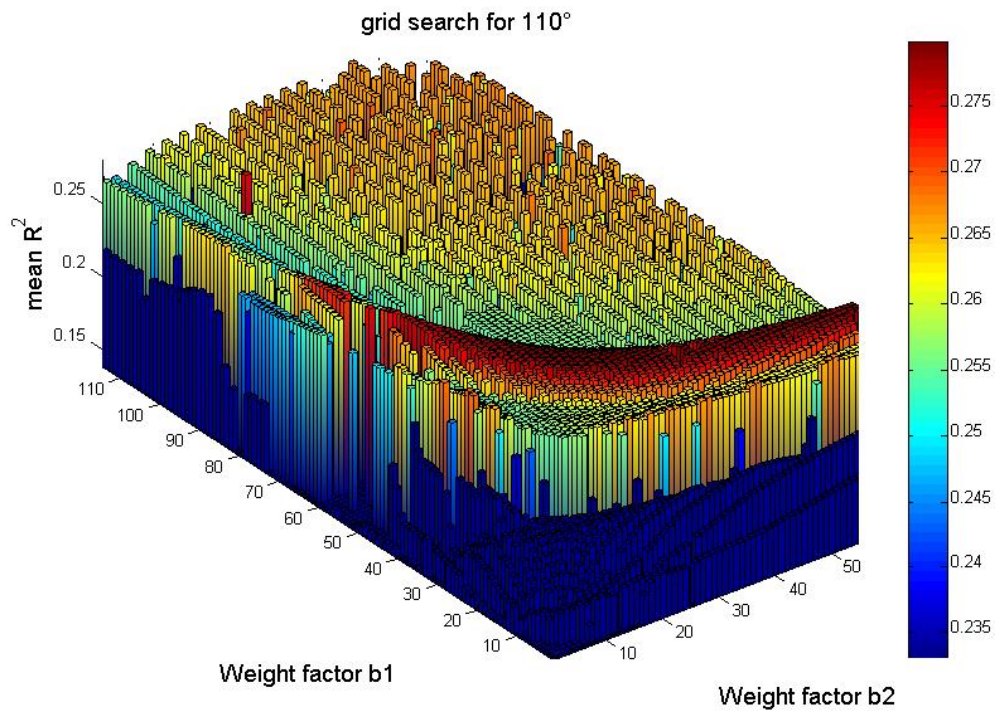
The force production of each muscle is generated by the DSEM. It is possible that the kinematic analysis the DSEM in inverse-dynamic mode uses for its determination of the load sharing has more difficulty at angles in retro flexion. The same can be said about the cost function. These are speculative remarks; they have not yet been looked during this study.



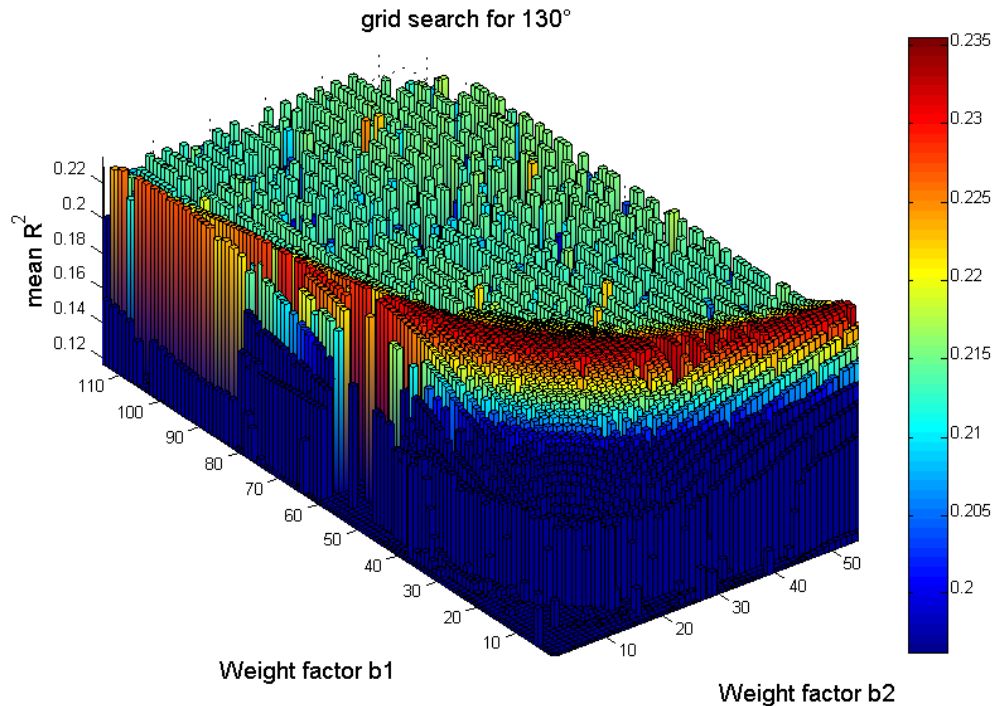
**Figure A - 2: Mean of the overall explained variance for all muscles at 70° of flexion. Highest R<sup>2</sup> (0.4244) was obtained at weight factors b<sub>1</sub>= 2 and b<sub>2</sub>= 48.**



**Figure A - 3: Mean of the overall explained variance for all muscles at 90° of flexion. Highest R<sup>2</sup> (0.3954) was obtained at weight factors b<sub>1</sub>= 2 and b<sub>2</sub>= 59.**



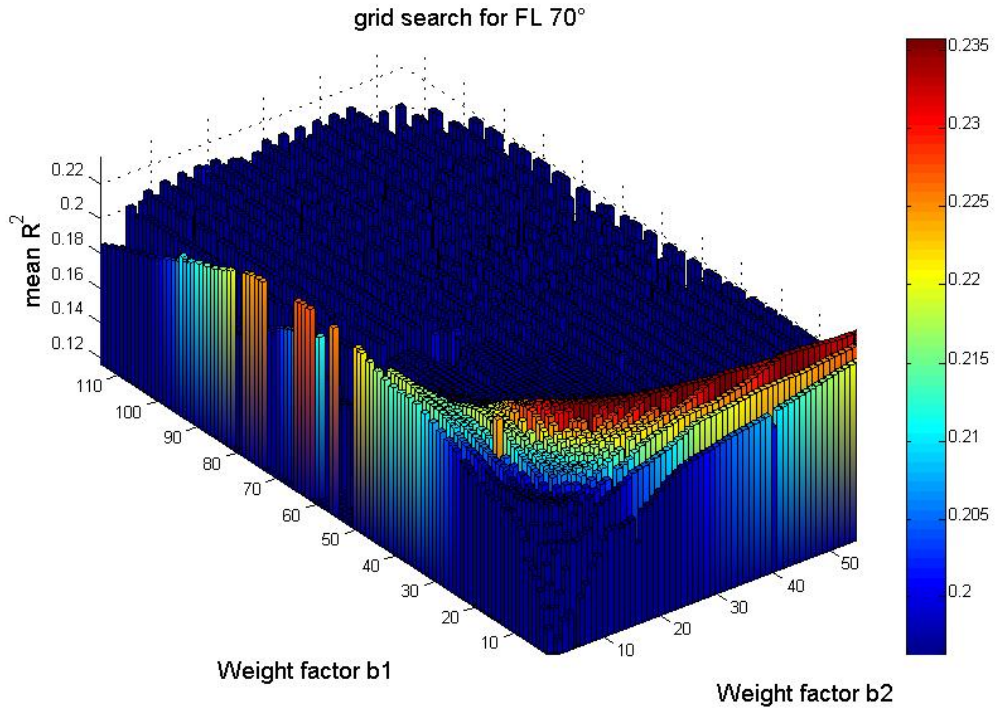
**Figure A - 4: Mean of the overall explained variance for all muscles at 110° of flexion. Highest R<sup>2</sup> (0.2789) was obtained at weight factors b<sub>1</sub>= 25 and b<sub>2</sub>= 19.**



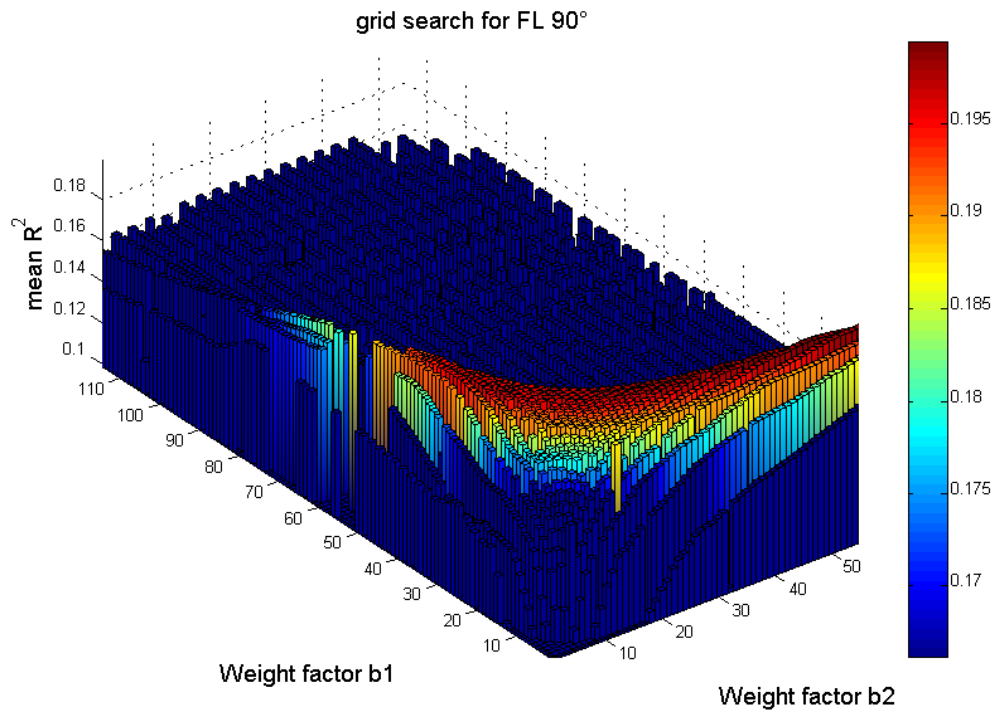
**Figure A - 5: Mean of the overall explained variance for all muscles at 130° of flexion. Highest  $R^2$  (0.2353) was obtained at weight factors  $b_1= 28$  and  $b_2= 21$ .**

### Flexors vs. extensors

In this section the overall results were divided in the explained variance retrieved by the flexor and extensor muscles at different angles. The overall consensus is that flexors show a worse linear relationship than extensors. Flexors do show better optimisation susceptibility. It is clear from Figure A - 9 that an optimum range of weight factors is present. What is interesting to see that for flexors, an increase in elbow flexion changes the optimum range. The combination of weight factors for measurements performed at 130° (Figure A - 9) show that the optimum weight factors are higher ( $b_1= 28$  and  $b_2= 21$ ) than at 70° ( $b_1= 7$  and  $b_2= 19$ ) (Figure A - 6). The reason for this outcome is unclear. Next to this finding, extensors show a worsen optimisation susceptibility. The overall explained variance is higher and it may be that when the linear relationship is high, significant improvements are less by varying the weight factors. Noteworthy are the extensors measured at 130° show a different general outcome. There is not a range present for this grid search and the higher the weight factors, the better the muscle activity is linearly related to the force produced.

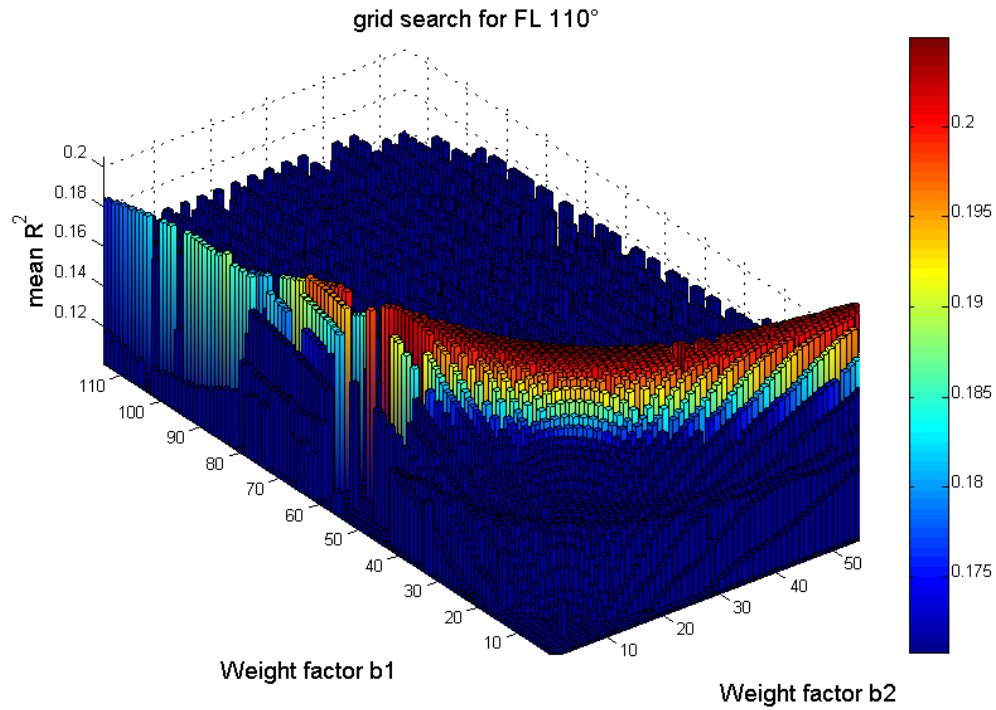


**Figure A - 6: Mean of the overall explained variance for flexor muscles at 70° of flexion. Highest R<sup>2</sup> (0.2357) was obtained at weight factors  $b_1=7$  and  $b_2=19$ .**

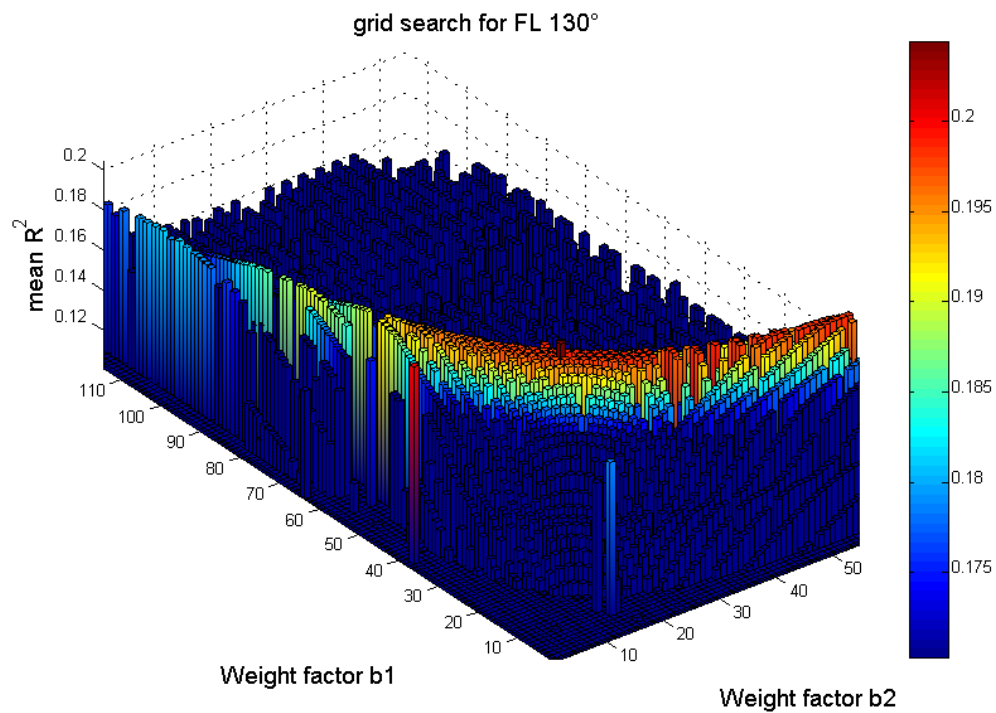


**Figure A - 7: Mean of the overall explained variance for flexor muscles at 90° of flexion. Highest R<sup>2</sup> (0.1994) was obtained at weight factors  $b_1=4$  and  $b_2=60$ .**

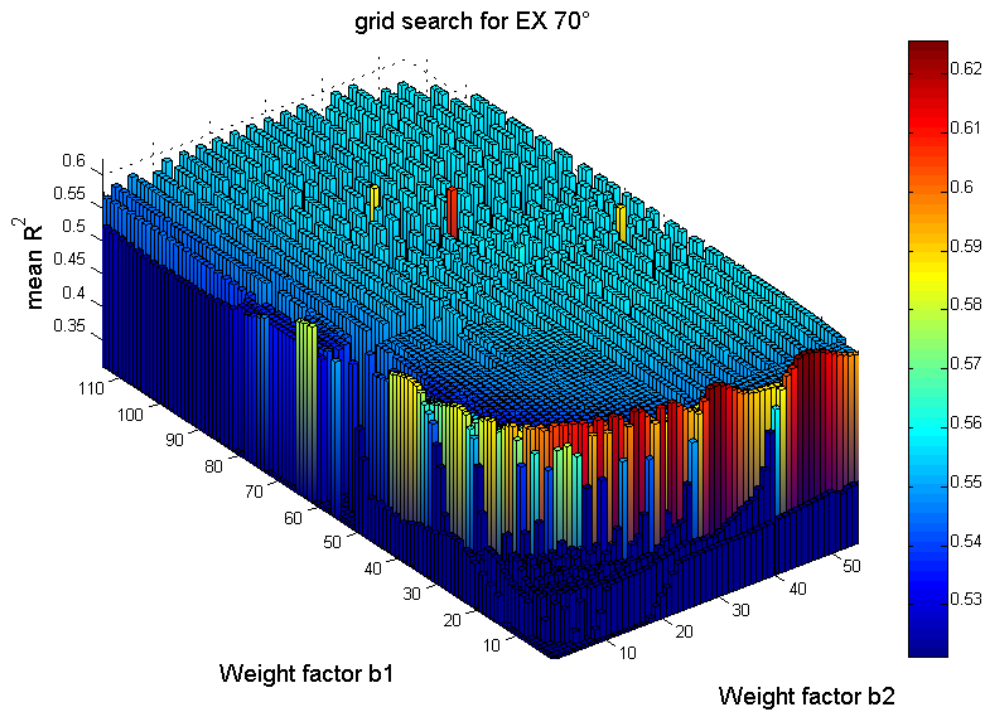




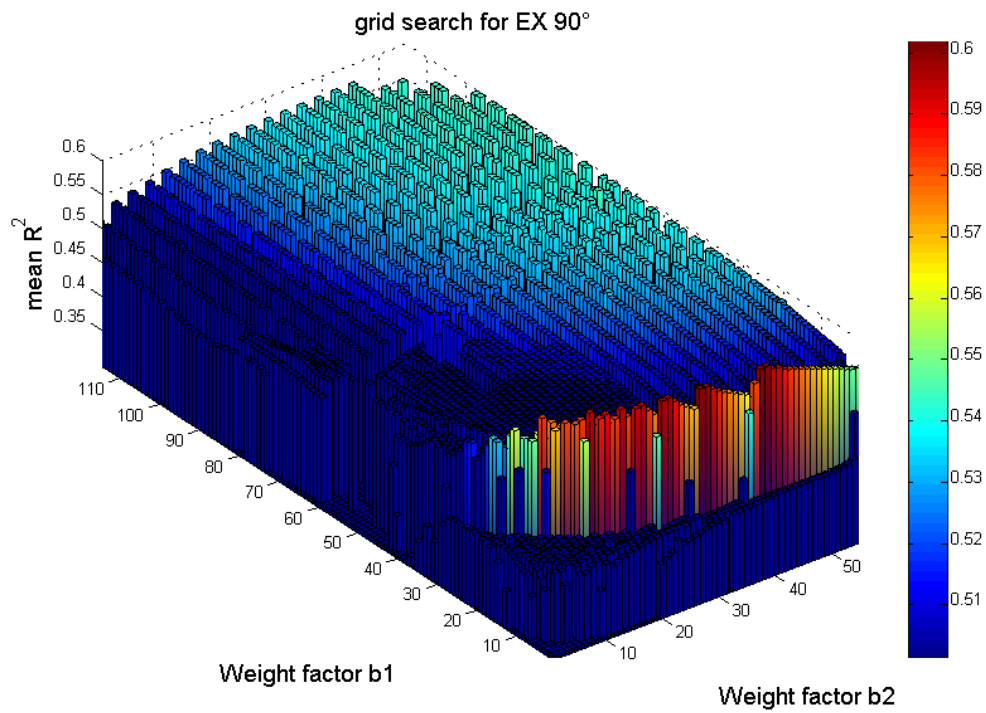
**Figure A - 8: Mean of the overall explained variance for flexor muscles at 110° of flexion. Highest R<sup>2</sup> (0.2048) was obtained at weight factors b<sub>1</sub>= 27 and b<sub>2</sub>= 48.**



**Figure A - 9: Mean of the overall explained variance for flexor muscles at 70° of flexion. Highest R<sup>2</sup> (0.2043) was obtained at weight factors b<sub>1</sub>= 28 and b<sub>2</sub>= 21.**

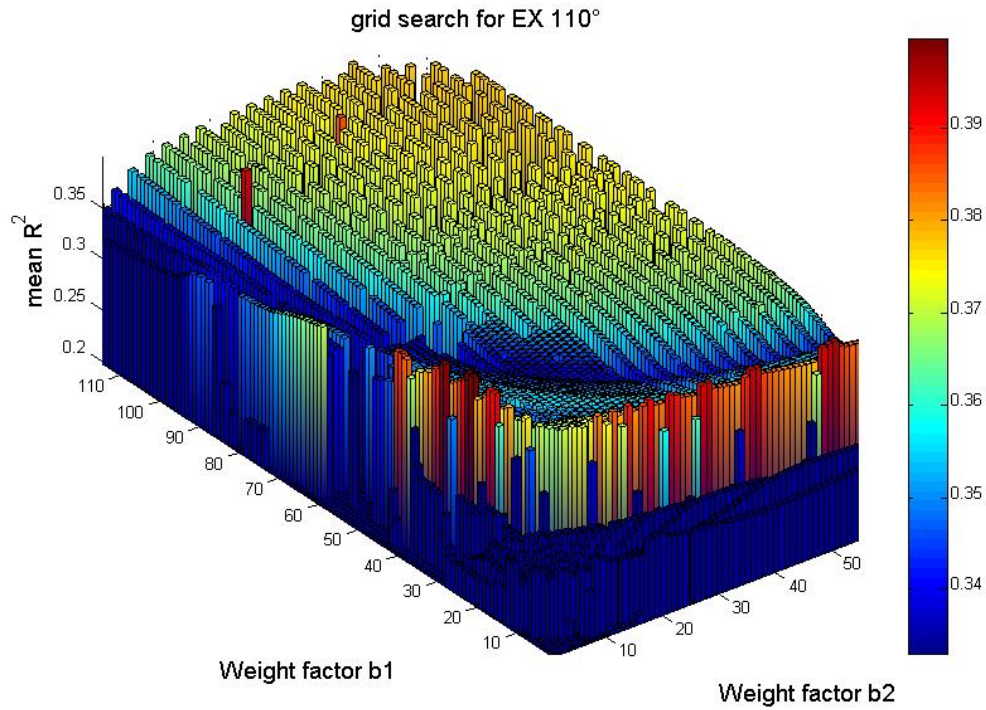


**Figure A - 10: Mean of the overall explained variance for extensor muscles at 70° of flexion. Highest R<sup>2</sup> (0.6254) was obtained at weight factors  $b_1= 2$  and  $b_2= 46$ .**

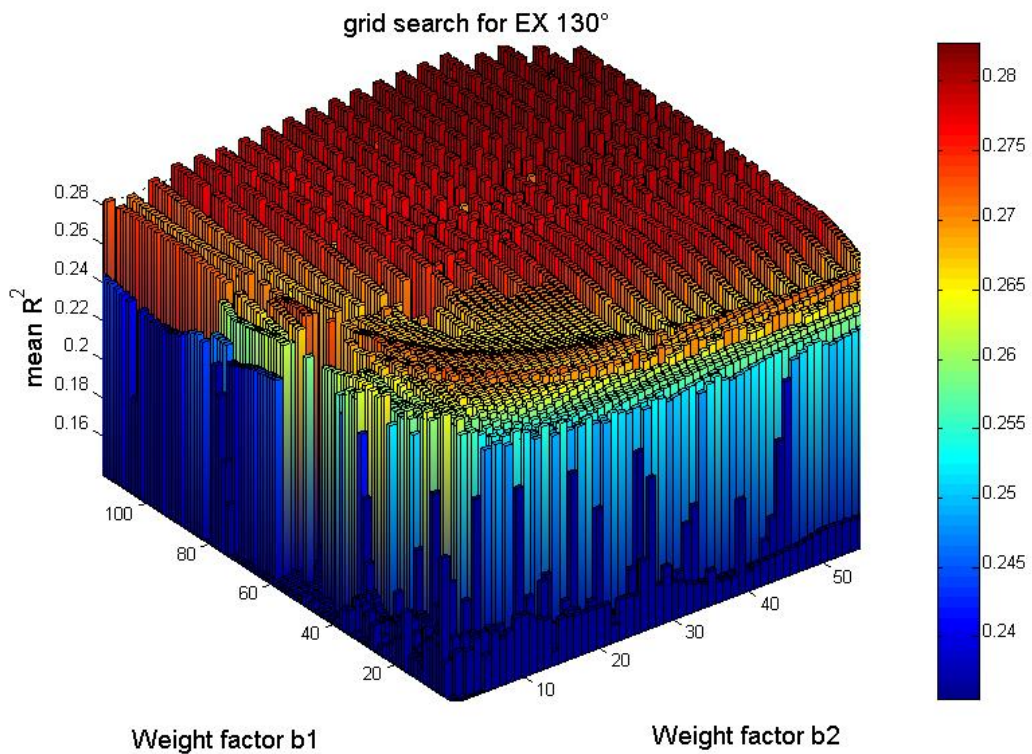


**Figure A - 11: Mean of the overall explained variance for extensor muscles at 90° of flexion. Highest R<sup>2</sup> (0.6019) was obtained at weight factors  $b_1= 2$  and  $b_2= 59$ .**





**Figure A - 12: Mean of the overall explained variance for extensor muscles at 110° of flexion. Highest R<sup>2</sup> (0.3996) was obtained at weight factors b<sub>1</sub>= 28 and b<sub>2</sub>= 5.**

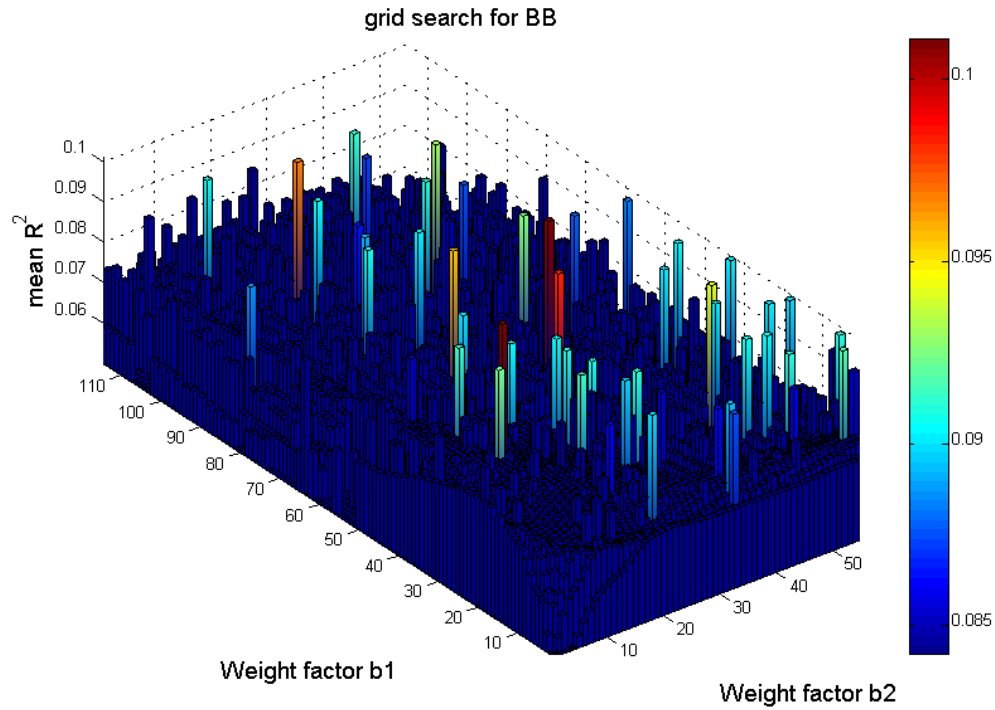


**Figure A - 13: Mean of the overall explained variance for extensor muscles at 130° of flexion. Highest R<sup>2</sup> (0.2895) was obtained at weight factors b<sub>1</sub>= 96 and b<sub>2</sub>= 28.**

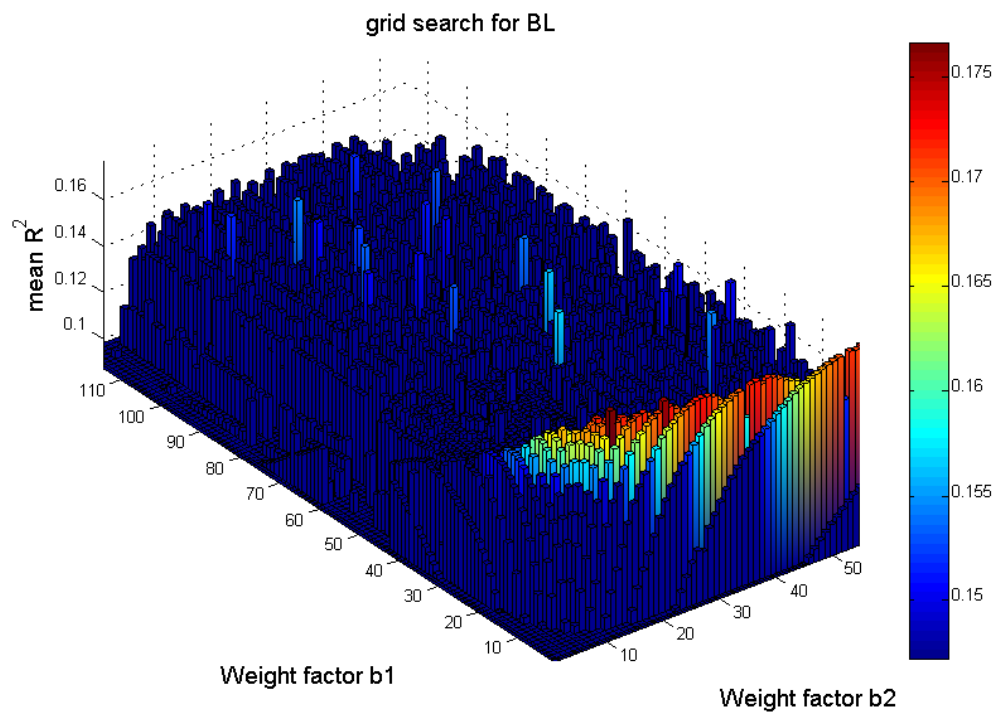
## **Individual muscles**

What the effect is of varying the weight factors on the explained variance of the individual muscles used for the overall analysis are shown in the figures below.

For the musculus biceps brachii (Figure A - 14) it is safe to say that the muscle activity and the force generated from the DSEM are not linearly related. The highest explained variance obtained is 0.1011. This already became clear when analysing the scatter plot of the two measures for this muscle. A large scatter was observed. Although this study is limited to only one test subject, initial scatter plots were analysed for more than one. Here, the same scatter became apparent. Therefore, it is less likely that the results obtained here are due to a random measurement error. There was no basis to through the results for the short head out. When comparing the muscle activity of the short head to the adjacent long head, no scatter was found. The same was found for the comparison of the outcome of the DSEM. The improvement that can be made here is most likely to be in the description of this muscle used by the model. For the m. brachii caput longum (Figure A - 15) the explained variance is low as well. There is a combination of weight factors that show some improvement as the colour spectrum might indicate.

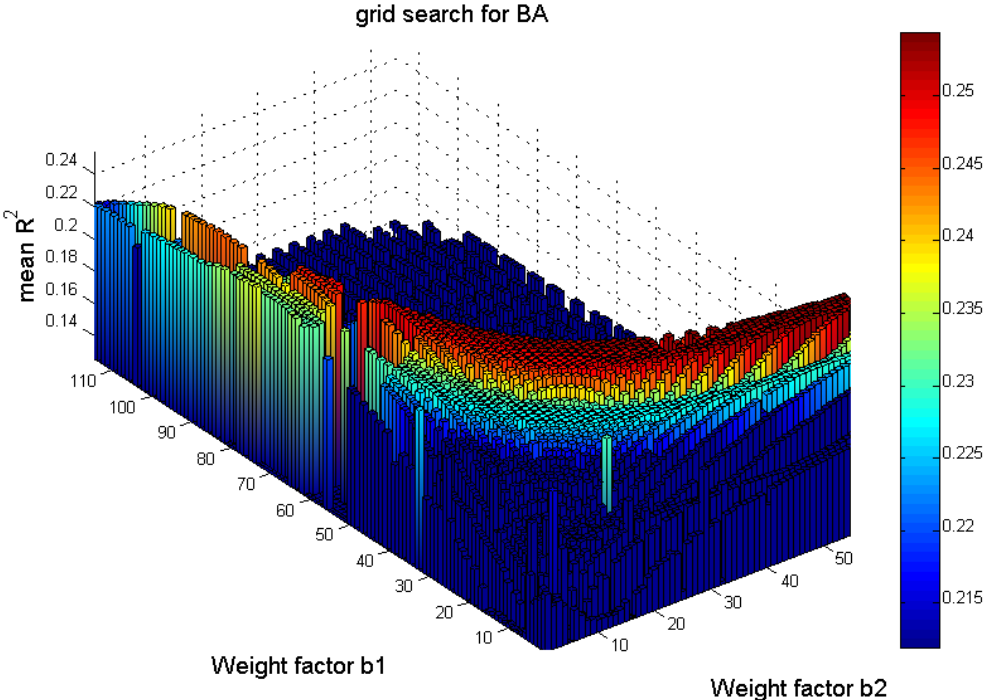


**Figure A - 14: The explained variance for m. biceps caput breve for all degrees of flexion. Highest R<sup>2</sup> (0.1011) was obtained at weight factors b<sub>1</sub>= 37 and b<sub>2</sub>= 17.**

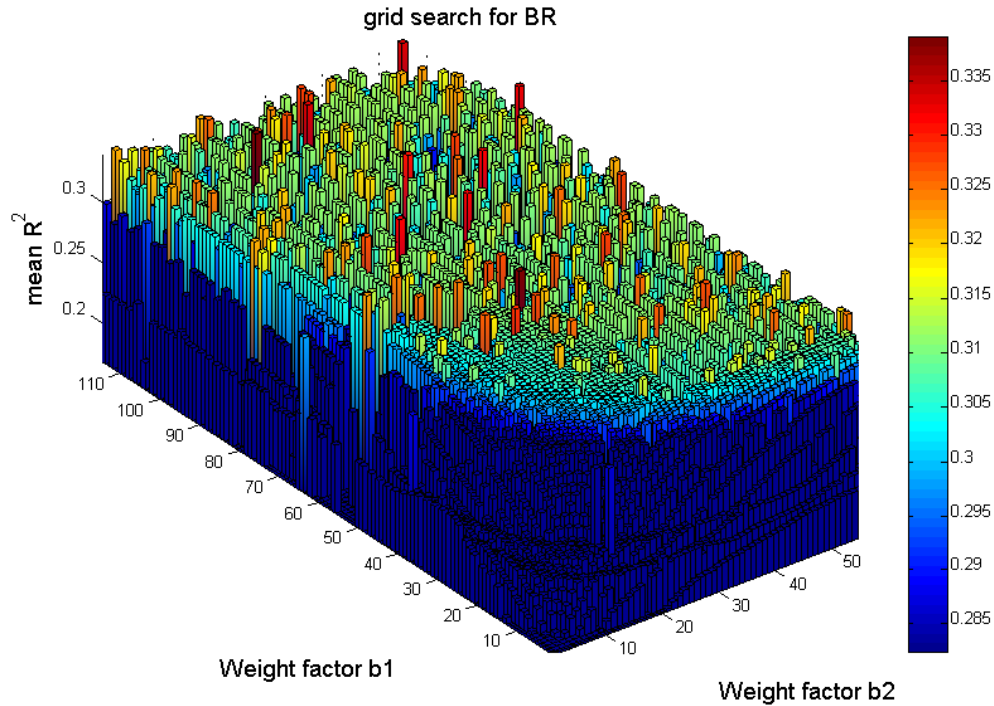


**Figure A - 15: The explained variance for m. biceps caput longum for all degrees of flexion. Highest R<sup>2</sup> (0.1766) was obtained at weight factors b<sub>1</sub>= 7 and b<sub>2</sub>= 15.**

Musculus brachialis (Figure A - 16) and brachioradialis (Figure A - 17) show the highest explained variance of all flexors. For the m. brachialis a clear optimised range of weight factors becomes apparent. Increasing the weight factors significantly decreases its linearity between activity and generated force. The m. brachioradialis does not seem to be susceptible to optimisation.

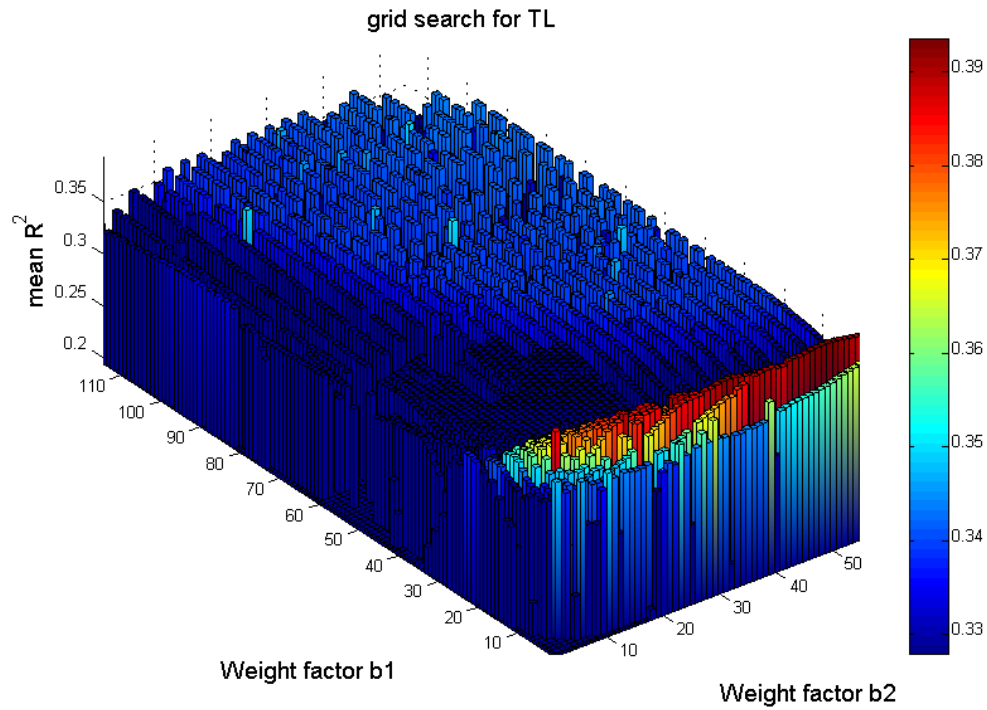


**Figure A - 16: The explained variance for m. brachialis for all degrees of flexion. Highest R<sup>2</sup> (0.2542) was obtained at weight factors b<sub>1</sub>= 10 and b<sub>2</sub>= 57.**

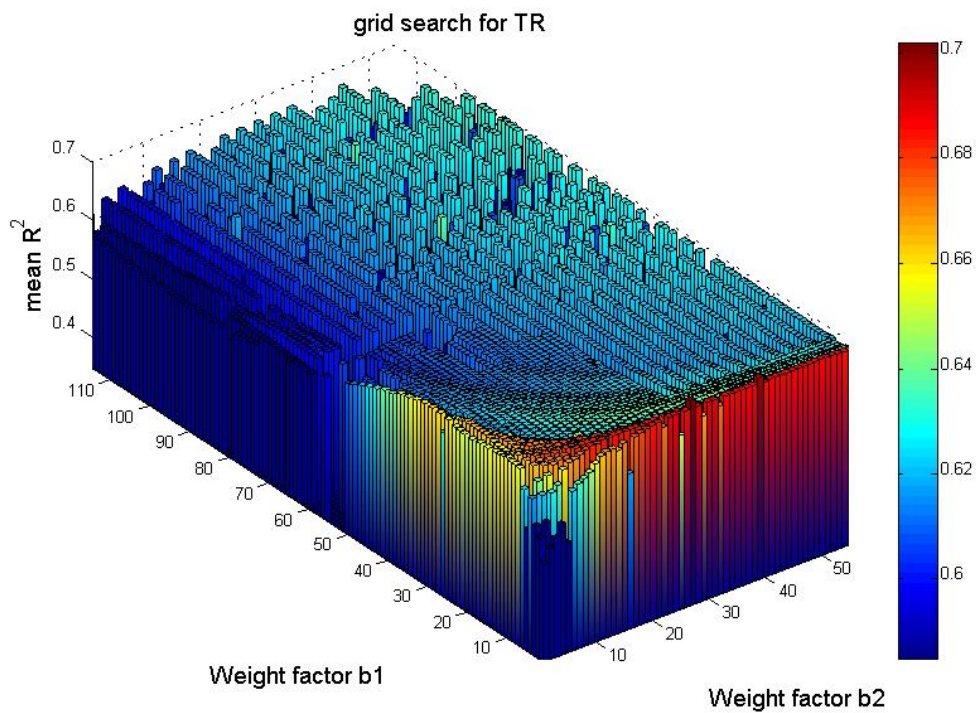


**Figure A - 17: The explained variance for m. brachioradialis for all degrees of flexion. Highest  $R^2$  (0.3389) was obtained at weight factors  $b_1= 106$  and  $b_2= 22$ .**

Results obtained from the triceps show that the muscle activity and generated forces from the DSEM are well linearly related. The muscles are least susceptible to optimisation. Musculus triceps mediale (Figure A - 18) is hard to measure by means of EMG. A small part is exposed to sensors and lies deep in fatty tissue. Crosstalk factors must be taken into account when analysing this muscle. The explained variance is therefore significantly lower for this head compared to the other heads.

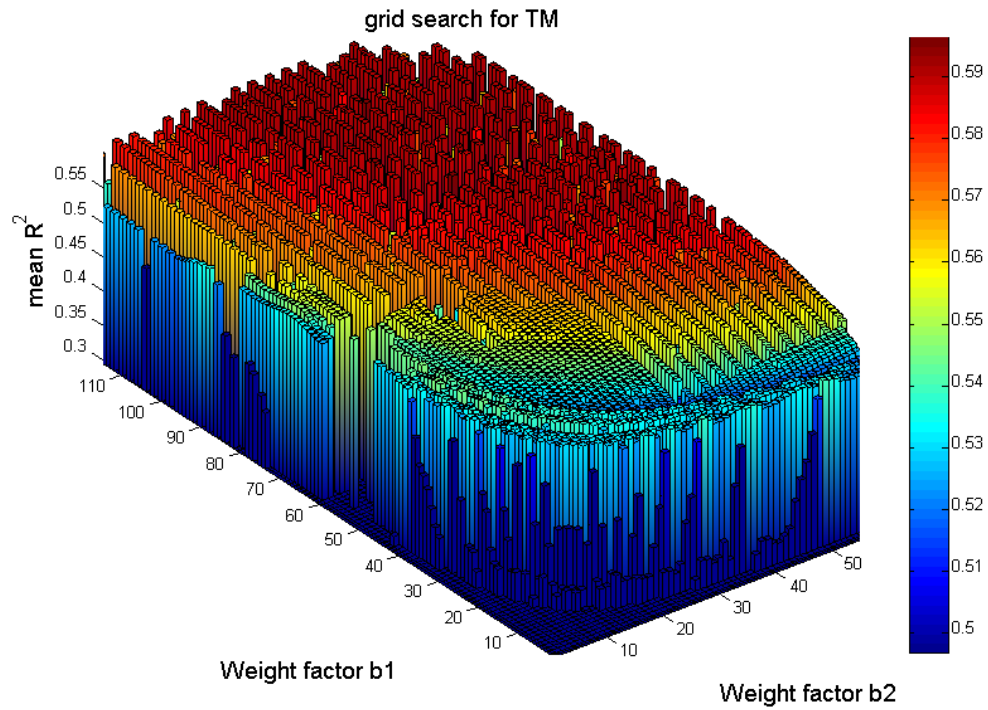


**Figure A - 18: The explained variance for *m. triceps caput laterale* for all degrees of flexion. Highest  $R^2$  (0.3934) was obtained at weight factors  $b_1=2$  and  $b_2=49$ .**



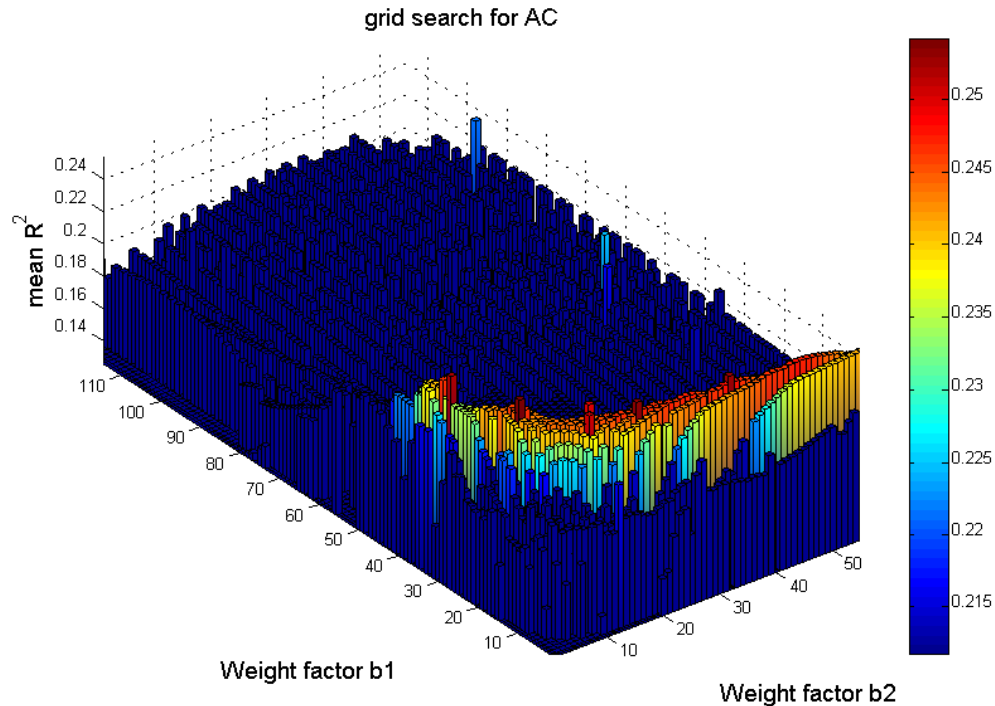
**Figure A - 19: The explained variance for *m. triceps caput longum* for all degrees of flexion. Highest  $R^2$  (0.7017) was obtained at weight factors  $b_1=1$  and  $b_2=27$ .**





**Figure A - 20: The explained variance for m. triceps caput mediale for all degrees of flexion. Highest  $R^2$  (0.5959) was obtained at weight factors  $b_1= 78$  and  $b_2= 37$ .**

The anconeus (Figure A - 21) is a small sized muscle and hard the measure. An optimum range of weight factors is present for this muscle.



**Figure A - 21: The explained variance for m. anconeus for all degrees of flexion. Highest R<sup>2</sup> (0.2541) was obtained at weight factors b<sub>1</sub>= 17 and b<sub>2</sub>= 6.**

### Concluding remarks

The overall results were analysed for different angles, flexor and extensor muscle at different angles and for individual participating muscles. The analysis compares the muscle activity to the generated forces from the DSEM. There are drawbacks of measuring muscle activity by means of electromyography (EMG). First, the relationship between muscle activation and the force it produces is unknown. Higher muscle activation leads to a higher force production, but the precise principle is unknown. Therefore, a critical note should be placed at the analysis method here since it assumes a linear relationship between the two measures. Different analysis methods were tried that assume if one measure increases, the other should increase as well. Although this may result in lower analysis values, it will describe the agreement between the two measures better and it might show a more consistent grid search outcome among different muscles.

Next, an important source of error in interpreting surface EMG is what is known as crosstalk. It is known that the amount of crosstalk depends on the

thickness of the subcutaneous layer, the detection system and non-propagating signal components (Hug 2010). Crosstalk factors vary among test subjects and different poses the arm assumes at which the muscles are measured. Therefore, it is plausible that the muscle activity measured when the humerus is in retro flexion is less accurate and this finding can be taken into account for defining a new measurement protocol.

The force production of each muscle is generated by the DSEM. It is possible that the kinematic analysis the DSEM in inverse-dynamic mode uses for its determination of the load sharing has more difficulty at angles in retro flexion. The same can be said about the cost function. These are speculative remarks; they have not yet been looked during this study.