AN INTRODUCTION TO THE STUDY OF
SKELETAL CORRELATIONS
IN THE N.Z. ROMNEY MARSH.

Norman Lamont.

BEING THE THESIS SUBMITTED BY "CHIRP"
FOR THE ANIMAL HUSBANDRY SECTION OF THE
# AN INTRODUCTION TO THE STUDY OF SKELETAL CORRELATIONS IN THE N.Z. ROMNEY MARSH.

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PART 1.

FOREWORD.

When this work was undertaken it was quite impossible to have anticipated the difficulties that were encountered. It soon became apparent however, that the approach to a new study involved a great deal of work of a collateral nature, having little direct bearing on the actual object of the investigation. In particular it was necessary to become generally familiar with certain branches of statistical method and to become very fully acquainted with the real significance of certain mathematical devices.

Statistical studies consumed the greater proportion of the time available for this work with the result that only a portion of the information contained in the data could be extracted. Indeed, a complete analysis of the data collected and recorded, using the methods evolved in this paper, would itself involve many months' work.

However, since the development of the analytical methodology has no direct bearing on the subject of skeletal correlations the paper has been divided into two parts.

Part 1 deals with the measurements made and the interpretation and discussion of the correlation coefficients that were calculated.

In Part 11 has been collected, all those considerations which were essentially incidental to the investigation - that is, selection of material technique of measuring etc. and in particular, the discovery of appropriate analytical devices for treating the data.
AN INTRODUCTION TO THE STUDY
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INTRODUCTION.

Correlation may be defined as the degree of inter-relationship that exists between any two variables and it is measured by a mathematical device which expresses the tendency of the two variables to fluctuate in sympathy. This means, in the present work, the interrelationship between the size or shape of one portion of the sheep's skeleton and the size or shape of another portion and the extent to which variations in one portion are attended by variations in another.

Correlation relating to the sheep has been regarded as divisible into two types -

(a) Correlation of external with internal characters - that is, correlation between conformation and such characters as fattening qualities, constitution etc.

(b) Correlation between various external characters, that is, relating to the relationships between the portions of the sheep's skeleton which together constitute what is known as conformation. This paper deals with this type of correlation and seeks to discover whether there is any relationship between the sizes of such portions, e.g. length of head and the length of pelvis, etc.

A knowledge of correlations of both types forms part of the "stock-in-trade" of the breeder and breed standards in regard to conformation, are defined by breed societies on the basis of supposed correlations of type (a) above. It is probable that this standard type defines with fair accuracy, the ideal sheep from the utility point of view and it most certainly does so to a much greater extent than do the so-called "perfect types" of dairy cattle defined by their respective breed societies. It would, perhaps, be desirable that a scientific investigation be undertaken with regard to this type of correlation in sheep with a view to defining type standards of
excellence with greater accuracy, but it was felt that, at present, the greater service to breeders would be provided by information on the relationships between the component parts of the skeleton as measurable on live sheep. It was hoped that this would assist the breeder to attain the standard laid down by the breed society - a standard which, probably, would not be greatly modified by a scientific investigation of the nature of that mentioned above.

A series of measurements were made on twenty Romney ewes from the Massey Agricultural College wool experimental flock and the data so obtained subjected to appropriate mathematical analysis.

The measurements were, in themselves, a matter of considerable difficulty and it was discovered that a great deal depended on the skill of the investigator. The difficulty of measuring live sheep will be quite apparent and considerable care and patience was necessary in order to attain a reasonable degree of accuracy.

The selection of appropriate mathematical devices for the analysis of the data also required lengthy consideration. The value of statistical method applied to biological data is the subject of considerable controversy and there is no doubt that arbitrary/methodology can be legitimately applied to such data, only when due regard is paid to the possible limitations of the methods employed. It is essential to remember that mathematical methods can only be regarded as convenient modes of expression, not as infallible devices for discovering natural laws. Utter familiarity with the data is a prerequisite to successful deductions from the results of mathematical analysis. It was necessary, therefore, to obtain an understanding of the more common statistical devices and an understanding of the information contained in the data collected, in order to select from the former, the method which most accurately expressed the facts contained in the latter.
When an endeavour was made to fulfil the intentions expressed in the above paragraph, it was soon discovered that the matter was going to involve a great deal of study on questions with no direct bearing on skeletal correlations. It was realised that the limitations attendant on the application of mathematics to livestock work were very real and further, there is the feeling that many research workers in Animal Husbandry have either been unaware of those limitations or have preferred in order to produce to accept such methods superficially spectacular results.

In this work, the choice had to be made whether methods should be adopted with no more than a cursory enquiry as to their value or whether a vast amount of time was to be spent in the study and consideration of the applicability of the simpler statistical devices to the material in hand. Further, the fact was fully appreciated that such study might do no more than confirm conclusions reached in a much more casual manner and in this event, the only return for the work would be an increased understanding of the matter by the author.

On the other hand, the scientific investigation of skeletal relationships in sheep is an entirely new field of research and it was felt, that the only course to pursue was one which would ensure that a firm foundation was laid for future work by a thorough examination of the analytical methodology.

The scope of this work was also restricted to some extent, by the fact that in many cases it is impossible to express in precise terms of measurement all that is apparent to an expert judge of sheep. For example, a judge may see in the facial expression of an animal, indications of a lack of robustness which will enable him to forecast with considerable accuracy, the weaknesses of general conformation to be expected; again a look of "nervous excitement" is frequently seen in animals of poor fattening ability. Such indefinable impressions would obviously be obtained only by expert observers and it would be quite impossible to express them in mathematical terms.
When all the measurements had been made, an enquiry was undertaken with a view to discovering the more common beliefs held by breeders relating to correlations. This enquiry was postponed until after the completion of the measurements because it was realised that preconceived ideas may often unconsciously bias an investigator in a particular direction. The aim of this work is neither to prove nor to disprove beliefs current among breeders but to approach the question with an open mind, unbiased by expected relationships.

**The Measurements.**

In the majority of cases, the measurements will require no more description than the names and the numbers which refer to the diagrams. The difficulties have been discussed in Part 1 and in few cases, will additional remarks be necessary.

Figs 1 and 11 show the outline of a shorn ewe from the side and from the front; the reference points are shown by numbers. In order to avoid the confusion of too much detail on one diagram, a separate sketch (Fig 11) is given of the skeleton of a sheep, the actual points of reference being enclosed by small red circles. This sketch is not intended to be beyond criticism but is sufficiently accurate to show the position of reference points.

1. **Width of Nose.** Fig. 11; a --- a.

   In such small measurements as this, it is apparent that a very small actual error would be a large relative error. Actually this measurement was comparatively easy to make but most measurements of this size are not regarded with confidence.

2. **Width between eyes;** Fig 11; b --- b.

3. **Width of (outside) eye-setting;** Fig 11; c --- c.

4. **Width between ears.** Fig. 11; d --- d.

   This measure was made immediately in front of the ears.

5. **Width between shoulders points;** Fig 11; e --- e.

   This was a fairly difficult measurement to make and is therefore less reliable than most.
NOTE: The remainder of the measurements and their reference numbers are all to be found on Figs. 1 and 111.

6. Width between jaw points - point 5A on each side.

7. Length of face: 1 --- 2.


10. Poll to jaw angle: 3 --- 5A.


This measurement was attempted but it was found quite impossible to obtain reliable results.


This measurement also proved unreliable owing to lack of clear definition of the posterior border of the blade, due to the fact that it was held so closely to the body.


It will be seen that this measurement actually includes more than the humerus proper as it is made to the point of the elbow (olecranon process) as indicated in the diagram.


Strictly speaking this portion contains two bones, the radius and the ulna; the olecranon process (point 13) being part of the latter.


This really includes the carpal bones of the joint. It would have been preferable for point 14 to be below rather than above the carpals but a more clearly defined point of reference was obtained in the position indicated.


Not only was this measurement small (see remarks on width of nose) but also was very difficult to make. For similar reasons an attempt to measure pastern slope was also unsuccessful.

18. Length of pelvis (Hook to pin) 20 --- 22.

A clearly defined point at the thurl (acetabulum) was difficult to obtain for the above two measurements and no great confidence should be placed in them.

The thurl point was easier to locate from this angle.

This is of the same type as the humerus etc. - the measurement is named according to the principal bone but really includes more.

This measurement like "fore pastern" was quite unreliable.

During all measuring the sheep were standing on a concrete floor.

That is, the width through the body at point 18.

For obvious reasons this will be less reliable than the measurement immediately above.

This measurement was made immediately in front of the hooks.

This was taken from the outside boundary of each hook (point 20).
This measure was not easy to make and was taken between the most posterior "points" of the pin bones (22).

36. Girth.

Taken behind the elbow.

37. Height to hook; ground level to 20.

38. Height to pin; ground level to 22.


40. Angle of hook.

This is the angle enclosed by the points 23 to 24 to 25.

This measure is recorded but it is not felt that it can be relied on to any great extent but would be useful only in indicating future lines of investigation.

41. An endeavour was made to secure some expression of the development of the brisket but no reliable measure could be found.

42. It is necessary also that some method be evolved for measuring slopes (e.g. pelvis, shoulder, etc.) which will give reliable results. The method employed in this paper, although probably more accurate than direct measurement, is not considered to be entirely satisfactory.
THE MEASUREMENTS.

FIG. 1

FIG. 11
THE MEASUREMENTS.

FIG. 111

[ALL SKETCHES BY AUTHOR.]
<table>
<thead>
<tr>
<th>MEASUREMENTS</th>
<th>693</th>
<th>637</th>
<th>E276</th>
<th>E743</th>
<th>E569</th>
<th>E564</th>
<th>X921</th>
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<td>2.0</td>
<td>2.8</td>
<td>2.2</td>
<td>2.1</td>
<td>2.0</td>
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<td>2. Width between eyes</td>
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<td>2.7</td>
<td>2.7</td>
<td>2.8</td>
<td>3.2</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>3. Width outside eye-setting</td>
<td>4.8</td>
<td>5.3</td>
<td>4.9</td>
<td>5.5</td>
<td>5.3</td>
<td>5.0</td>
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<td>4. Width between ears</td>
<td>3.6</td>
<td>3.9</td>
<td>3.8</td>
<td>4.1</td>
<td>3.9</td>
<td>4.0</td>
<td>4.1</td>
</tr>
<tr>
<td>5. Width between points of jaw</td>
<td>3.6</td>
<td>3.4</td>
<td>3.7</td>
<td>3.8</td>
<td>3.6</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>6. Length of face</td>
<td>5.1</td>
<td>5.3</td>
<td>4.8</td>
<td>5.5</td>
<td>5.5</td>
<td>5.2</td>
<td>4.7</td>
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<td>7. Length of head</td>
<td>9.8</td>
<td>10.0</td>
<td>9.6</td>
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<td>10.3</td>
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<td>9.4</td>
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<td>8.2</td>
<td>7.4</td>
<td>7.7</td>
<td>7.8</td>
<td>7.7</td>
<td>7.7</td>
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<tr>
<td>9. Poll to jaw angle</td>
<td>5.8</td>
<td>6.1</td>
<td>6.0</td>
<td>6.2</td>
<td>6.0</td>
<td>5.8</td>
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<td>8.3</td>
<td>8.1</td>
<td>8.9</td>
<td>8.1</td>
<td>8.2</td>
<td>8.0</td>
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<td>11. Length of humerus</td>
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<td>6.7</td>
<td>6.3</td>
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<td>6.9</td>
<td>7.1</td>
<td>6.9</td>
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<td>12. Length of radius</td>
<td>7.0</td>
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<td>7.1</td>
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<tr>
<td>13. Length of fore-cannon</td>
<td>5.0</td>
<td>5.4</td>
<td>4.8</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
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<td>14. Length of pelvis</td>
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<td>9.3</td>
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<td>9.0</td>
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<td>8.9</td>
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<td>15. Hook to thurl</td>
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<td>5.0</td>
<td>5.2</td>
<td>5.0</td>
<td>5.2</td>
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<tr>
<td>16. Thurl to pin</td>
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<td>4.7</td>
<td>4.6</td>
<td>5.0</td>
<td>5.2</td>
<td>5.0</td>
<td>5.2</td>
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<td>17. Length of femur</td>
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<td>7.8</td>
<td>7.5</td>
<td>7.2</td>
<td>7.4</td>
<td>7.6</td>
<td>7.4</td>
</tr>
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<td>18. Length of tibia</td>
<td>10.0</td>
<td>10.4</td>
<td>10.3</td>
<td>10.3</td>
<td>10.3</td>
<td>10.3</td>
<td>10.7</td>
</tr>
<tr>
<td>19. Length of hind cannon</td>
<td>5.8</td>
<td>6.2</td>
<td>5.8</td>
<td>6.1</td>
<td>6.3</td>
<td>6.4</td>
<td>6.3</td>
</tr>
<tr>
<td>20. Length of thoracic vertebrae</td>
<td>9.6</td>
<td>10.7</td>
<td>9.9</td>
<td>11.8</td>
<td>9.8</td>
<td>10.7</td>
<td>9.8</td>
</tr>
<tr>
<td>21. Length of loin</td>
<td>7.8</td>
<td>8.1</td>
<td>7.4</td>
<td>8.3</td>
<td>8.2</td>
<td>7.8</td>
<td>7.5</td>
</tr>
<tr>
<td>22. Body depth</td>
<td>11.4</td>
<td>12.0</td>
<td>11.5</td>
<td>12.3</td>
<td>11.9</td>
<td>12.1</td>
<td>11.5</td>
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<tr>
<td>23. Wither height</td>
<td>23.9</td>
<td>26.0</td>
<td>25.7</td>
<td>24.7</td>
<td>24.4</td>
<td>24.1</td>
<td>22.2</td>
</tr>
<tr>
<td>25. Width between shoulder pt.</td>
<td>7.6</td>
<td>7.6</td>
<td>7.2</td>
<td>7.7</td>
<td>8.2</td>
<td>7.4</td>
<td>7.0</td>
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<tr>
<td>26. Width of body, (girth)</td>
<td>7.5</td>
<td>7.2</td>
<td>6.9</td>
<td>7.2</td>
<td>6.8</td>
<td>6.5</td>
<td>6.9</td>
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<tr>
<td>27. Length of body(last rib)</td>
<td>10.5</td>
<td>10.5</td>
<td>10.7</td>
<td>9.6</td>
<td>9.8</td>
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<td>9.4</td>
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<td>28. Width of loin (front)</td>
<td>4.7</td>
<td>5.2</td>
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<td>29. Width of loin (rear)</td>
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<td>31. Width between pins</td>
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<td>2.7</td>
<td>2.4</td>
<td>2.4</td>
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<tr>
<td>32. Girth</td>
<td>34.0</td>
<td>33.0</td>
<td>33.5</td>
<td>34.8</td>
<td>33.4</td>
<td>34.2</td>
<td>30.9</td>
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<tr>
<td>33. Height to hook</td>
<td>24.4</td>
<td>25.3</td>
<td>24.7</td>
<td>24.6</td>
<td>24.5</td>
<td>25.0</td>
<td>24.5</td>
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<tr>
<td>34. Height to pin</td>
<td>19.7</td>
<td>22.0</td>
<td>20.4</td>
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<td>20.3</td>
<td>20.5</td>
<td>20.1</td>
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<tr>
<td>35. Body length</td>
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<td>29.2</td>
<td>27.5</td>
<td>30.0</td>
<td>29.0</td>
<td>28.7</td>
<td>27.8</td>
</tr>
<tr>
<td>36. Angle of hook (in degrees)</td>
<td>128</td>
<td>133</td>
<td>128</td>
<td>122</td>
<td>131</td>
<td>128</td>
<td>130</td>
</tr>
<tr>
<td>37. Size index</td>
<td>27.1</td>
<td>28.3</td>
<td>27.3</td>
<td>28.6</td>
<td>28.1</td>
<td>28.0</td>
<td>26.2</td>
</tr>
</tbody>
</table>
THE RESULTS.

It is apparent that the maximum number of correlation coefficients that could be calculated from the data collected, would number many hundreds and since the time involved in the preliminary work was so great it was, unfortunately, necessary to limit the number of coefficients calculated.

As was mentioned earlier in this paper, an enquiry was made to discover the more common opinions held by breeders in regard to skeletal correlations. As a result of this enquiry, it appeared that the majority of ideas were concerned with the relation of various parts of the body to the length of the cannon and to head measurements.

It seemed appropriate, therefore, in selecting the limited number of coefficients to be calculated at present, to compute those which were apparently of greatest interest to breeders, viz. those relating to the cannon and to head measurements.

The general principles involved in the interpretation of the coefficients, are discussed in those sections (Part 11) which concern the development of suitable analytical devices for treating the data. The application of these principles to particular cases will not, therefore, require to be considered here in detail.

The results are summarised in tabular form below. As discussed in Part 11 the significance of a correlation coefficient depends on its relation to its probable error and in this work a simple expedient was adopted to save time from unnecessary calculation. As a result, the lowest significant coefficient was found to be ± 0.47. The effect of error of measurement is, however, to reduce the coefficients below their true value; it will be seen in the discussion that for this reason, coefficients smaller than ± 0.47 are regarded as significant.
**TABLE 1.**
CORRELATION COEFFICIENTS (r) BETWEEN "THE SIZE INDEX" AND VARIOUS MEASUREMENTS; WITH THE PERCENTAGE INDEPENDENT VARIABILITY (P.I.V.) OF THE LATTER.

<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>r</th>
<th>P.I.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of head</td>
<td>+0.81</td>
<td>59%</td>
</tr>
<tr>
<td>Length of face</td>
<td>+0.62</td>
<td>79%</td>
</tr>
<tr>
<td>Width (outside) eye-setting</td>
<td>+0.33</td>
<td>94%</td>
</tr>
<tr>
<td>Width between ears</td>
<td>+0.65</td>
<td>76%</td>
</tr>
<tr>
<td>Poll to jaw</td>
<td>+0.36</td>
<td>93%</td>
</tr>
<tr>
<td>Length of fore-cannon</td>
<td>+0.59</td>
<td>81%</td>
</tr>
<tr>
<td>Wither height</td>
<td>+0.82</td>
<td>57%</td>
</tr>
<tr>
<td>Body Depth</td>
<td>+0.62</td>
<td>78%</td>
</tr>
<tr>
<td>Length of shoulder-blade</td>
<td>+0.67</td>
<td>74%</td>
</tr>
<tr>
<td>Shoulder slope</td>
<td>-0.30</td>
<td>95%</td>
</tr>
<tr>
<td>Girth</td>
<td>+0.79</td>
<td>61%</td>
</tr>
<tr>
<td>Length thoracic vertebrae</td>
<td>+0.47</td>
<td>88%</td>
</tr>
<tr>
<td>Width body (at girth)</td>
<td>+0.54</td>
<td>84%</td>
</tr>
<tr>
<td>Width body (at last rib)</td>
<td>+0.39</td>
<td>92%</td>
</tr>
<tr>
<td>Height to hook</td>
<td>+0.69</td>
<td>72%</td>
</tr>
<tr>
<td>Hind cannon</td>
<td>+0.47</td>
<td>88%</td>
</tr>
<tr>
<td>Body length</td>
<td>+0.78</td>
<td>62%</td>
</tr>
<tr>
<td>Length of pelvis</td>
<td>+0.75</td>
<td>66%</td>
</tr>
<tr>
<td>Length of loin</td>
<td>+0.49</td>
<td>87%</td>
</tr>
<tr>
<td>Width between hooks</td>
<td>+0.66</td>
<td>75%</td>
</tr>
<tr>
<td>Pelvis slope</td>
<td>-0.02</td>
<td>100%</td>
</tr>
<tr>
<td>Ratio head length to width of (outside) eye-setting</td>
<td>+0.44</td>
<td>89%</td>
</tr>
</tbody>
</table>

+ The "percentage independent variability" is obtained by using Sumner's factor (see Part 11).
### Table 11.
**Gross and Net Correlation Coefficients Between "Length of Fore Cannon" and Other Measurements.**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gross r.</th>
<th>Net r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Length of face</td>
<td>+0.48</td>
<td>+0.18</td>
</tr>
<tr>
<td>(2) Length of head</td>
<td>+0.59</td>
<td>+0.24</td>
</tr>
<tr>
<td>(3) Poll to jaw</td>
<td>+0.27</td>
<td>+0.08</td>
</tr>
<tr>
<td>(4) Length of pelvis</td>
<td>+0.60</td>
<td>+0.30</td>
</tr>
<tr>
<td>(5) Length of hind-cannon</td>
<td>+0.69</td>
<td>+0.58</td>
</tr>
<tr>
<td>(6) Length of thoracic vertebrae</td>
<td>+0.39</td>
<td>+0.16</td>
</tr>
<tr>
<td>(7) Length of loin</td>
<td>+0.33</td>
<td>+0.06</td>
</tr>
<tr>
<td>(8) Body depth</td>
<td>+0.47</td>
<td>+0.16</td>
</tr>
<tr>
<td>(9) Wither height</td>
<td>+0.52</td>
<td>+0.08</td>
</tr>
<tr>
<td>(10) Width body (at girth)</td>
<td>+0.22</td>
<td>-0.15</td>
</tr>
<tr>
<td>(11) Width body (at last rib)</td>
<td>-0.01</td>
<td>-0.32</td>
</tr>
<tr>
<td>(12) Width between hooks</td>
<td>+0.18</td>
<td>-0.35</td>
</tr>
<tr>
<td>(13) Girth</td>
<td>+0.25</td>
<td>-0.44</td>
</tr>
<tr>
<td>(14) Width of (outside) eye setting</td>
<td>+0.34</td>
<td>+0.19</td>
</tr>
<tr>
<td>(15) Body Length</td>
<td>+0.66</td>
<td>+0.40</td>
</tr>
<tr>
<td>(16) Pelvis slope</td>
<td>-0.03</td>
<td>-0.02</td>
</tr>
<tr>
<td>(17) Shoulder slope</td>
<td>-0.13</td>
<td>+0.06</td>
</tr>
</tbody>
</table>

### Table 111.
**Gross and Net Correlation Coefficients Between "Length of Head" and Other Measurements.**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gross r.</th>
<th>Net r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Length of face</td>
<td>+0.84</td>
<td>+0.73</td>
</tr>
<tr>
<td>(2) Body depth</td>
<td>+0.51</td>
<td>+0.02</td>
</tr>
<tr>
<td>(3) Width body (at girth)</td>
<td>+0.48</td>
<td>+0.09</td>
</tr>
<tr>
<td>(4) Width body (last rib)</td>
<td>+0.36</td>
<td>+0.08</td>
</tr>
<tr>
<td>(5) Shoulder slope</td>
<td>-0.28</td>
<td>-0.07</td>
</tr>
<tr>
<td>(6) Pelvis length</td>
<td>+0.64</td>
<td>+0.10</td>
</tr>
</tbody>
</table>
### TABLE IV
GROSS AND NET CORRELATION COEFFICIENTS BETWEEN "WIDTH OF (OUTSIDE) EYE-SETTING" AND OTHER MEASUREMENTS.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gross r.</th>
<th>Net r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Width between ears</td>
<td>+0.28</td>
<td>+0.09</td>
</tr>
<tr>
<td>(2) Width body (at girth)</td>
<td>+0.02</td>
<td>-0.20</td>
</tr>
<tr>
<td>(3) Width body (at last rib)</td>
<td>-0.01</td>
<td>-0.16</td>
</tr>
<tr>
<td>(4) Width between hooks</td>
<td>-0.02</td>
<td>-0.34</td>
</tr>
</tbody>
</table>

### TABLE V
GROSS AND NET CORRELATION COEFFICIENTS BETWEEN THE RATIO OF "HEAD LENGTH" TO "WIDTH OF (OUTSIDE) EYE-SETTING" AND OTHER MEASUREMENTS.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gross r.</th>
<th>Net r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Fore cannon</td>
<td>+0.24</td>
<td>-0.03</td>
</tr>
<tr>
<td>(2) Body depth</td>
<td>+0.02</td>
<td>-0.36</td>
</tr>
<tr>
<td>(3) Body width (at girth)</td>
<td>+0.40</td>
<td>+0.21</td>
</tr>
<tr>
<td>(4) Body width (at last rib)</td>
<td>+0.32</td>
<td>+0.18</td>
</tr>
<tr>
<td>(5) Width between hooks</td>
<td>+0.36</td>
<td>+0.10</td>
</tr>
</tbody>
</table>

### TABLE VI
GROSS AND NET CORRELATION COEFFICIENTS BETWEEN "WIDTH BETWEEN EARS" AND OTHER MEASUREMENTS.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gross r.</th>
<th>Net r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Body width (at girth)</td>
<td>+0.09</td>
<td>-0.41</td>
</tr>
<tr>
<td>(2) Body width (at last rib)</td>
<td>+0.14</td>
<td>-0.16</td>
</tr>
<tr>
<td>(3) Width between hooks</td>
<td>+0.36</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

### TABLE VI1
GROSS AND NET CORRELATION COEFFICIENTS BETWEEN "POLL TO JAW" AND OTHER MEASUREMENTS.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gross r.</th>
<th>Net r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Body depth</td>
<td>+0.20</td>
<td>-0.03</td>
</tr>
<tr>
<td>(2) Girth</td>
<td>-0.02</td>
<td>-0.53</td>
</tr>
<tr>
<td>TABLE V</td>
<td>SUNDRI GROSS CORRELATIONS.</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td>1. Length of head - wither height</td>
<td>+0.69</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - girth</td>
<td>+0.60</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - height to hook</td>
<td>+0.53</td>
<td></td>
</tr>
<tr>
<td>2. Length of pelvis - wither height</td>
<td>+0.65</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - girth</td>
<td>+0.38</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - height to hook</td>
<td>+0.59</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - body length</td>
<td>+0.74</td>
<td></td>
</tr>
<tr>
<td>3. Wither height - Height to hook</td>
<td>+0.64</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - girth</td>
<td>+0.54</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - body length</td>
<td>+0.46</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - scapula</td>
<td>+0.59</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - humerus</td>
<td>+0.13</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - radius</td>
<td>+0.46</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - fore cannon</td>
<td>+0.52</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - shoulder slope</td>
<td>-0.55</td>
<td></td>
</tr>
<tr>
<td>4. Height to hook - body length</td>
<td>+0.44</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - femur</td>
<td>+0.61</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - tibia</td>
<td>+0.67</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; &quot; - hind cannon</td>
<td>+0.57</td>
<td></td>
</tr>
<tr>
<td>5. Girth - body length</td>
<td>+0.49</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; height to hook</td>
<td>+0.25</td>
<td></td>
</tr>
</tbody>
</table>
DISCUSSION.

In Table 1 it is seen that, as would be expected, most measurements exhibited high correlation with general size. However, if we accept the validity of Sumner's factor (see Part 11), it appears that even fairly high correlation with general size allows a portion a considerable amount of independent variability. If the percentage of "net" to "gross" standard deviation (column headed P.I.V., Table 1) is high it means in Sumner's own words that - "the greater part of the variation in the size of these structures is independent of variations in the size of the body as a whole".

Hence, it appears that the various parts of the sheep provide comparatively flexible material on which the breeder may work. The contribution of any portion to general size may vary between sheep of the same general size and so give rise to differences of type among sheep that conform to the same general standards. The sheep measured in this work exhibited wide variation in general conformation but it was found that the variation of each separate part was by no means as great as expected. It appears then, that the wide variation in general conformation was due to the aggregate effect of small and indiscriminate variations in many parts, rather than to large variations in a few.

On the other hand, however, while this plasticity of material increases the possible different types of conformation that could be evolved, it renders the immediate task of the breeder very complex and difficult. It means that, to a large extent, each portion must be considered as a separate unit in the blending of parts into a well-balanced whole.

This brings us to the real aim of this paper which is to discover relationships between parts and so reduce the number of separate factors that the breeder requires to consider. The method of analysing the data to secure the best expression of such relationships is discussed in detail in Part 11, so that only the bare conclusions reached need be mentioned here.
Gross correlation coefficients in the Tables 11, 111, etc. are of little value as their magnitude is largely due to the sympathetic variation that is superimposed to a greater or less degree on all portions, in accordance with their relationship with size.

"Net" or "partial" coefficients have, therefore, been calculated; these express the relationship between any two portions which is independent of their mutual relationship to size.

The manner in which general size variation may obscure true relationships, is strikingly exemplified in the case of the correlation between cannon length and girth in Table 11. It is seen that the gross coefficient between these two portions, though not significant, is definitely positive, while on eliminating the "size factor" a significant negative correlation is obtained. It is possible also that some correlations believed by breeders to exist, are really "gross correlations"; that is, the supposed mutual relationship is merely the result of a fairly high correlation between each portion and the general size of the animal. For example it will be seen that "length of head" and length of pelvis are both very highly correlated with general size (+0.81 and +0.75. respectively), and the fairly high gross correlation between them i.e. +0.64 would be expected. However, on calculating the partial coefficient the mutual relationship is shown to be artificial and only due to the common relationship of the two parts to size. It is interesting to note in this connection that the majority of breeders interviewed, believed that this correlation did exist and only one was definitely of the opinion, supported by this work, that no real relationship existed.

It will be seen from a perusal of the tables that most relationships are of the same type as the above and that most of the portions considered are capable of variation independent of other parts. However, there are some "net" relationships which appear to exist and in the following paragraphs only
"net" correlations are referred to, except where specifically mentioned otherwise.

A common belief among breeders, which is supported by this work, is that a sheep with a long cannon bone will be "long-bodied" and "slab-sided". In Table 11 it is seen that a significant negative correlation (net) exists between cannon-length and girth; also definite indications of negative correlation with width of body and positive correlation with body length. The correlations between cannon length and pelvis dimensions are barely significant when considered separately but a coefficient of +0.30 with length of pelvis and -0.32 with width between hooks may be regarded as justifying the statement that a long cannon means a narrow shaped pelvis.

On the other hand, the breeders opinion that a long cannon is associated with a straight shoulder is not borne out by this investigation. The coefficient between cannon and shoulder slope does not depart significantly from zero but, as pointed out elsewhere, the latter measurement is not very reliable so that this matter had best be left open. Also the opinion that length of cannon and length of head are correlated is not supported as the value +0.24 cannot be considered significant.

Definite opinions were also expressed by many, concerning relationships between head length and other portions. The probable reason for these opinions has been discussed above and Table 111 shows that this work fails completely to substantiate breeders' opinions on this point; the only significant coefficient, being the very high one with length of face which would be expected.

It might be emphasized here that the net coefficients, which are being discussed, relate to actual, not relative measurements i.e. "length of head" refers to the actual length of this portion and not to relative length or shape. The other dimensions of the head are dealt with separately and
finally the actual shape of the head is considered.

It appears from Table IV that the shape of the head about its long axis can vary as no correlation is found between width of (outside) eye-setting and width between ears. Other correlations with width of eye-setting do not reach significance although that with width between hooks suggests a tendency to negative correlation - (which is contrary to expectation).

A similar position is revealed in the case of width between ears and body width (at girth). In Table V1 a negative coefficient (-0.41) which closely approaches significance is found between these two portions. It is quite contrary to expectation to find that increase in width between ears is attended by a probable decrease in body width at girth but no explanation can be offered. It is probable however, that an explanation would be forthcoming if a study of the growth rates of these parts were made.

No opinions were expressed by breeders in regard to correlations between depth of head and other portions and it is interesting to note therefore in Table V11 that there is a definite negative correlation between the poll to jaw measurement and girth.

When breeders' opinions were sought in regard to correlations between head measurements and other portions, it was found difficult to distinguish those concerned with actual dimensions and those concerned with the shape of the head.

In order to investigate this point, coefficients were calculated between various portions and the ratio of "length of head" to "width outside eye-setting" (Table V). Only one of the coefficients calculated differed from zero by anything approaching significance and that was a negative figure - 0.36 between the ratio and body depth; meaning that a sheep which has a narrow head will lack depth.

In Table V111 sundry gross correlation coefficients are recorded. These have little real value, for reasons indicated
above, but they are recorded as their calculation was incidental to other parts of the work.

It will be noted that there is indication of negative correlation between wither heights and shoulder slope. As this is of considerable practical interest the net coefficient was calculated and found to be -0.56. That is to say, a high wither is correlated definitely with a straight shoulder.

It is fully realised that the above discussion merely touches a small section of a very big field. The few points mentioned above represent an exceedingly small proportion of the information that could be extracted from the data already collected. Restrictions of time, unfortunately, prevented further calculation but the above points indicate the principles involved, so that the extraction of further information from the data given, would be almost entirely a matter of mechanical calculation of the correlation coefficients.
CONCLUSION.

The aim of this paper was to open up a new field of research which would provide the breeder with more exact information in regard to skeletal correlations. Briefly, we may regard the task of the breeder as two-fold; not only must he seek to breed an animal in which each portion is of the desirable shape but also must all parts be blended together so as to form a well-balanced whole.

It is apparent that, if definite relationships between parts were found to exist, it would simplify the breeders' task by reducing the number of separate and independent factors that he is required to consider. As a result of this investigation, it is felt that there is little likelihood of such a hope being realised to an unqualified extent. Certain relationships have been established which should be of some assistance to the breeder but few are of a sufficiently high order to justify the propounding of definite rules from them.

As emphasized in other parts of this paper, a significant correlation coefficient does no more than indicate the direction which more specialised investigation should take and cannot be regarded as proof in itself, of the existence of definite causal relationships.

Hence it is suggested that extensions of this investigation be made in conjunction with detailed studies of growth rates of various parts of the sheep's skeleton. The conformation of a sheep is really a function of the differential growth rates of the parts and at any particular stage of its life, the shape of its skeleton may be regarded as a "cross-section" of the growth rates of the various parts of that skeleton.

This work deals with the animal at maturity and the existence of significant correlation between two parts suggests therefore, that just prior to the onset of maturity
and consequent cessation of growth, there existed a mutual relationship between the growth rates of the two portions; consequently it is to be expected that studies of skeletal correlations would require to be made conjointly with growth rate studies if a full understanding is desired of the fundamental causes of differences in conformation.
ACKNOWLEDGMENTS.

It would be impossible to name all those members of the College Staff, fellow students and others to whom thanks are due for criticisms and suggestions.

In particular, however, the author wishes to record his thanks to Mr. W.N. Paton and Mr. A.W. Hudson, both of the Department of Agriculture, whose criticisms and advice on matters relating to statistical method were invaluable.
AN INTRODUCTION TO THE STUDY OF
SKELETAL CORRELATIONS IN THE N.Z. ROMNEY MARSH.

PART II.
FOREWORD.

It is quite obvious that the value of any investigation finally depends on the care with which the ground has been prepared. Particularly does this apply in the present work which is opening up a new field of research and a great deal of consideration has been given to the general procedure adopted and in particular to the statistical devices used. In the case of both these points, but in particular the latter, very little assistance was available in the form of precedents established. Furthermore, there is no doubt that there are definite limitations in the use of precise mathematical formulae when applied to the analysis of relatively abstruse biological phenomena.

For these reasons, what is generally an incidental part of an investigation, has, in the present instance, become a most important section of the paper and a separate part has been devoted to it.
In such work as this, it is apparent that the validity of the results will depend, not only on the method of obtaining and analysing the data but, to an even greater extent, on the appropriateness of the material used. This, in turn, will depend on the care employed in ensuring that all relevant factors have been considered and catered for, in selecting the "sample" of sheep on which the measurements were made. In this connection it is necessary to consider the theoretical basis of correlation.

It is realised that to go fully into this matter would lead to discussion of an involved and rather speculative nature, and the following is merely intended to briefly outline the position in order to render more apparent the significance of the sampling considerations in later paragraphs.

Let us assume that a significant positive correlation between two characters A and B has been calculated from a number of casually selected sheep and consider what may be the cause of this relationship.

1. "Species" correlations.

The two characters A and B may be the expression of the same hereditary factor or of very closely "linked" hereditary factors that were present in and have been handed down from the ancestors of all modern sheep. It is possible, too, that A and B, if not genetically related, have become fixed in/natural selection. It is possible therefore, that such correlations would be encountered in all breeds of sheep.

2. "Breed" correlations.

In addition to the above, a further cause of correlation would be the fixing of the two characters, in the process of evolution of the Romney as a breed. That is to say, the characters A and B, though genetically unrelated, may both have been considered desirable by the founders of the breed. The effect of constant selection would then be to cause an association between these two characters.

This process of association of characters by deliberate selection is one that has, of course, persisted to the present day, with the result that in certain strains we may expect to find correlations peculiar to those strains; such correlations being established by a consistent breeding programme or by the extensive use of a very prepotent sire by the breeder who established or maintains that strain.

It is obviously impossible to draw a sharp distinction between "Breed" and "Strain" correlations as the difference is manifestly one of degree rather than of essence. However, it was hoped that as far as possible "strain" correlations would be eliminated and only those discovered which were "species" or "breed" correlations and which would, therefore, be applicable to the breed as a whole and not merely to any one strain.

It would be an interesting and valuable extension of this work to conduct an investigation into some of the more prominent stud flocks in order to discover the correlations existing in each and then to analyse such data as a whole. At present, however, in opening up the subject of skeletal correlations, it was felt that efforts should be directed towards the discovery of the more fundamental relationships which would, in any case, be the logical preliminary to a more specialised investigation.
(a) Selection of Sample.

The fundamental principles in sampling are that the sample shall represent all factors contributing to the matter under review and shall be free from all factors that may lead to erroneous conclusions. The "matter under review" in this paper is correlations of parts insofar as they are common to all members of the Romney breed.

On first thoughts it may seem impossible to obtain a representative sample of the Romney breed which is free from "strain correlations" except by carefully selecting individual sheep from each strain. Not only would such a method result in expense and inconvenience through having the material scattered over a wide area but also it is quite unnecessary.

Briefly, the point hinges on the fact that what is required is not a sample of typical Romney sheep but a sample of the true correlations inherent in the Romney breed. A little consideration will show that poorness of type from the breeders point of view cannot affect the existence of true inherent correlations. Whereas good quality sheep will evidence true and also "artificial" or strain correlations, only the former will exist in a flock more or less indiscriminately bred from the conformation aspect and such a flock was found conveniently at hand in the College wool experimental flock. This flock has been accumulated from various sources on the sole basis of fleece type displayed and has been bred without any consideration being paid to conformation; that is, both with reference to its source and to its maintenance this flock can be regarded as "indiscriminately bred" in regard to conformation.

Assume for the purpose of discussion that a true inherent correlation exists between shortness of cannon and good spring of rib. This would not only mean that a short cannon would be associated with a well sprung rib but also that a long cannon would be associated with a poor spring of rib. In other words a true relationship would be apparent irrespective of the actual
length of cannon or the actual spring of rib - it would be
evident in good quality animals or in poor quality animals that
were "long-shanked" and "slab-sided".

On the other hand, assume there is no true inherent correlation
between cannon length and spring of rib. In an indiscriminately
bred flock the lack of correlation would be revealed by
investigation; but a short cannon and a well sprung rib are both
desirable characters in the breeder's eyes and he would endeavour
to eliminate their opposites by culling. The tendency would be
therefore for two such desirable characters to become associated
in a well bred flock purely as a result of the breeder's efforts
and not because of any inherent relationship.

For these reasons it is considered that significant correlation
based on data obtained from the wool experimental flock will be
applicable to the Romney breed as a whole; if these calculations
show no correlation between two characters, it means that mutual
relationship is not common to the breed and, whether it exists
in a particular strain, can only be decided by a special investi­
gation.

Two further points considered in relation to the selection
of the material were sex and age. The existence of a typical
masculine and a typical feminine conformation is undisputed.
Such differences depend largely on different proportions between
parts in each sex and it is possible that the same true correlations
would be common to both. However, the investigation of such
relationships would need to be undertaken separately for each
sex, as the existence of different proportions between parts would
be a disturbing factor if the sexes were mixed. In the present
work, therefore, the investigations were confined to ewes.

It will be seen below that it was necessary to eliminate the
effect of heterogeneity of size amongst the sheep measured.
The effect of age must, however, be considered apart from its
effect of general size, because, as is well known, the ratios
between parts vary at different stages of growth. For this
reason it was necessary that the sheep measured be approximately of the same age. Furthermore, the effects of external factors such as nutrition are more apparent when the sheep are still growing; if a growing animal receives a check due to nutrition or disease, the effect of that check will be most apparent while the animal is young and as maturity approaches there will be a tendency for the animal to recover the lost ground. In order to eliminate such factors as far as possible, the sheep chosen were all mature ewes, aged 4th or 6th.

In selecting the sample of sheep on which to work, it has been seen that certain influences had to be eliminated viz. "strain" correlations, sex and age, in order to ensure that the material employed was appropriate to the matter that was being studied. In accordance with the principles of sampling, a random selection of twenty was made from sheep in the wool experimental flock which satisfied the above special conditions.

(b) Size of Sample.

The second essential in sampling is that the sample be large enough to ensure that conclusions based on it are applicable to the whole. Strictly speaking, it is impossible to regard "adequacy" of sample as distinct from representativeness. The former is often used to refer to the size of the sample but it is obvious that size is really one of the factors that determine "representativeness". In a sense the sample must be large enough to adequately represent the amount of variation between the individuals.

A formula is provided by statisticians for testing "adequacy", based on the relation of the probable error of the mean of the sample to the standard deviation. It is considered that the sample is adequate if the standard deviation is at least six times the probable error of the mean. A consideration of the value of such arbitrary tests is not within the scope of this paper; suffice to say, that the application of this test to the sheep used, showed that they provided a theoretically adequate sample. Furthermore, it was found that twenty sheep were more than sufficient to occupy the time available for this work.
COEFFICIENT OF CORRELATION.

The degree of correlation between any two variables is expressed as a correlation coefficient. Perfect positive correlation is indicated by a coefficient of +1.0, lack of correlation by a zero coefficient and perfect negative correlation by a coefficient of -1.0. In practice, however, a coefficient of unity, positive or negative, is rarely obtained and certain rules have been evolved for interpreting the coefficient. These rules vary slightly among different authorities but the following represent the general opinion:-

(1) Significant correlation is indicated where the coefficient (accepted symbol $r$) is at least four times its probable error.

(2) When $r$ is 0.3 and the probable error is sufficiently small, it is regarded as indicating moderate correlation. A coefficient of less than 0.3 is of doubtful significance.

(3) When $r$ is 0.5 and the probable error sufficiently small, there is evidence of decided correlation.

The coefficient of correlation is obtainable from various formulae which have been evolved for various purposes. The two most commonly used which were considered in the present work are:-

(1) Coefficient of concurrent deviations.

This is obtained from the formula -

$$ r = \pm \sqrt{\frac{2c}{n} - \frac{n}{n}} $$

$c$. = Number of concurrent deviations.

$n$. = Number of pairs of items.

This method measures the tendency of the items of each series to deviate in a like direction from their respective means; it is concerned only with the directions of the deviations and not with their size. The attractiveness of this coefficient is its simplicity but it is apparent that it would not be very reliable where, as will be seen later, a certain amount of personal error is involved. It would be possible for "personal error" to cause a deviation to be very slightly on the wrong side of the mean and
by this method such a deviation would be given as much weight as one whose position was unquestionable.

(\(\bar{y}\)) Pearsonian coefficient.

This method, evolved by Pearson, is that most commonly employed in statistical work and is subject only to the restriction that it is not applicable to any but linear or nearly linear relationships. There is no apparent reason for expecting that relationships in the present work should depart from the linear to any extent, if at all. Scatter graphs are at best difficult to interpret but when these were plotted (see later) there were no indications of definite non-linear relationships.

Furthermore the Pearsonian coefficient is designed to reflect the magnitude as well as the directions of the deviations and despite the somewhat laborious calculations involved, it was decided to employ it in this paper.

The coefficient is calculated from the formula -

\[ r = \frac{\sum d_x \cdot d_y}{N \cdot \sigma_x \cdot \sigma_y} \]

\[ \sum d_x \cdot d_y \] = the algebraic sum of the products of the deviations of each pair of variables from their respective means.

\[ N = \] the number of paired items.

\[ \sigma_x \text{ and } \sigma_y = \] the standard deviations of the variables.

The following example of the method of calculation of the coefficient indicates how it expresses the tendency of the variables to fluctuate in sympathy -

(a) Method of Calculation of Correlation Coefficient.

Gross correlation between wither height and fore cannon.
<table>
<thead>
<tr>
<th>Wither x</th>
<th>Fore Cannon y</th>
<th>Devnx</th>
<th>Devny</th>
<th>Product dx·dy</th>
<th>Devns. ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.9</td>
<td>5.0</td>
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<td>-</td>
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<td>+.22</td>
<td>.308</td>
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<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>.010</td>
<td>-</td>
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<td>.008</td>
<td>- .16</td>
</tr>
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<td>+.7</td>
<td>+.12</td>
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<td>- .49</td>
</tr>
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<td>5.5</td>
<td>+1.2</td>
<td>+.22</td>
<td>.264</td>
<td>-1.44</td>
</tr>
</tbody>
</table>

488.0 105.6 - - 1.72² 0.192 14.42 0.6120

Mean \( x \) = \( \frac{488.0}{20} = 24.4 \) Inches. \( \sigma_x = \sqrt{\frac{14.42}{20}} = 0.849 \)

Mean \( y \) = \( \frac{105.6}{20} = 5.28 \) Inches. \( \sigma_y = \sqrt{\frac{612}{20}} = 0.175 \)

\( dx\cdot dy = 1.72² - 0.192 = +1.530. \)

\( r = 20 \times 0.849 \times 0.175 = +0.52\)
(b) Interpretation of coefficient.

An exact interpretation of the term "correlation" is difficult to make and the statistical literature studied did not provide a satisfactory definition. However, some observations can be made which will indicate the conception of correlation held by the author and, therefore, the conception on which the discussions in this work are based. The purpose of these observations is primarily to render the results of this work more intelligible to those who are not familiar with correlation coefficients; but there is also reason to believe that many, who are more or less familiar with correlation work, are inclined to attribute a significance to the coefficients in excess of that which is strictly justified. For these reasons it was felt that some brief observations on the point would not be out of place.

For the sake of simplicity the discussion below deals with positive coefficients but the remarks apply, of course, equally well to negative coefficients and it is necessary simply to substitute for the latter, "opposite" for "same" direction of deviation.

It appears that a significant positive coefficient may be regarded as indicating that there is a tendency for the two variables to fluctuate in sympathy, but that the relationship is not an invariable one but only a general rule. This point will be apparent from inspection of the example above where it will be seen that concurrency between the deviations is only general not invariable.

It is very difficult to go beyond this point in defining the properties of a correlation coefficient and some authorities appear to avoid doing so. It is stated however, that a significant positive correlation means that a change in one variable is likely to be accompanied by a change in the second, in the same direction and of like magnitude; presumably the degree of "likelihood" depends on the actual size of the
coefficient. The statement has already been made that concurrency as regards direction of deviation is only a "likelihood" and it seems probable, therefore, that concurrency in regard to the magnitude of the deviations involves a still greater element of doubt. Indeed, even the term "like magnitude" required comment. Consider for example two series of values $A$ and $B$ as given below; the coefficient between these would be $+1.0$ i.e. perfect positive correlation.

$$\begin{align*}
A & : 14 : 12 : 10 : 8 : 6. \\
B & : 16 : 13 : 10 : 7 : 4
\end{align*}$$

The deviations of the $A$ variables are two units and of the $B$ variables, three units but actually the deviations are of "like magnitude" when considered in relation to the range of variation - the range of $A$ variables being 8 units and that of $B$, 12 units.

It will be seen, also, from the above example that the ratio of $A : B$ varies from greater to less than unity. So that perfect positive correlation does not necessarily mean that the ratio between the parts is constant.

It will be apparent that an accurate definition of a correlation coefficient is difficult, if not impossible, to make. Readers may feel that the above brief discussion has confused rather than clarified their conception of correlation. In a sense, this is the purpose of the discussion; to emphasize the impossibility of attributing specific and rigid properties to the coefficient. We are not justified in regarding the coefficient in any but the broad sense - that of a measure of general tendency to sympathetic fluctuation - and the exact nature of the relationship or its cause cannot be deduced from the coefficient itself but requires further investigation.

(c) Probable error of the coefficient.

It has already been pointed out that the significance of the correlation coefficient depends in part on its probable error; the coefficient is required to be at least four times its probable error to be considered significant.
The probable error of the correlation coefficient is calculated from the formula -

\[ P.E. = \frac{0.6745 \ (1 - r^2)}{\sqrt{N}} \]

where \( r \) = the correlation coefficient.
\( N \) = the number of sheep.

A simple expedient can be adopted to save time from calculating the probable error of each coefficient. It is seen that the lowest significant value for \( r \) is that which satisfies the equation -

\[ r = 4 \times \frac{0.6745 \ (1 - r^2)}{\sqrt{N}} \]

Since \( N \) is constant throughout this work, \( r \) is the only unknown and it is then simply a matter of solving the quadratic equation. The value for \( r \) so obtained was 0.47 and this is the lowest value for \( r \) which can be regarded as significant in the present work.

(d) The calculations.

It will be readily appreciated that the mathematical calculations involved in this work would in themselves require a very great deal of time. It was considered essential, however, that the author should become thoroughly familiar with the methods themselves in order to gain some appreciation of their limitations and ensure that the analytical devices employed gave a reasonably accurate reflection of the physical facts. The particular problems encountered in this work have not yet received the critical attention of statisticians and their solution required considerably more time than could be anticipated. This, unfortunately, left little time for the interpretation of the results except in so far as their general interpretation would follow from the discussion of the methods. Nevertheless, it was felt that the cautious course pursued was a much wiser one than endeavouring to draw conclusions from results obtained by a method whose reliability had not been thoroughly investigated.
TECHNIQUE OF MEASURING.

The original intention was to cover the sheep in as much detail as possible and a list of nearly fifty items was accordingly drawn up. It was hoped that this would be merely a preliminary survey and that a condensed list of measurements would be compiled as a result of the experience so obtained and extended over a larger number of sheep. Measurements were to be eliminated which were too difficult to be reliable and for which alternatives could be obtained; further, it was thought that some correlations would be unquestionable and extension to a larger number of sheep would only be necessary in doubtful cases. It soon became obvious, however, that this hope had been based on a lack of appreciation of the difficulties ahead. The only sound basis for discrimination between measurements would be a thorough understanding of the data already collected; this involved the estimation of personal error by repeating all measurements and also the discovery of suitable analytical devices for treating the data.

In other words, it was discovered that the preliminary work in entering an entirely new field of research - that of skeletal correlations in sheep - was, in itself, a project that would fully occupy the few months available.

(a) Difficulties encountered.

The principal difficulties encountered in the actual measuring of the parts and the manner in which they were met, are given below.

(1) Location of points.

The difficulties consequent on making the measurements on live sheep can readily be appreciated and not the least of these, was that of obtaining points of reference which could be located with accuracy in different sheep. In few cases were the ends of bones sharply delineated and considerable care and patience was necessary in acquiring the necessary skill. A few days were spent before the main work was actually
commenced, in becoming familiar with the points of reference, the measurements so obtained being discarded. It soon became apparent that in some cases it would be necessary to sacrifice strict anatomical detail in order to obtain well defined points of reference. (See Fig 111). It was felt, however, that this was warranted since the approach to the subject was primarily from the breeder's conception of conformation.

The effect of this difficulty of locating points on the accuracy of measurements, depended largely on the skill of the investigator although a certain amount of assistance was obtained by the use of simple instruments to be considered below.

(2) Wool and curvature.

These two may be considered together as they both prohibited the use of a plain rule or tape measure. It would be difficult to measure with rule or tape the distance between two points on a more or less flat surface when those points, even apart from their covering of wool, were not visible but had to be located by touch. Where there was an actual curvature between the points and also a covering of wool the use of tape or rule was manifestly impossible if an accurate "straight-line" measurement was to be obtained.

It was fortunate that the work was done in the late summer when the ewes were not in very good condition. Beyond rendering the location of points a little more difficult, condition was not really a serious problem in view of the methods employed.

(3) Stance.

When the individual measurements are considered it will be seen that in very few cases could the stance of the animal affect the reading. As far as possible, however, the sheep were held in a normal standing position to eliminate the possibility of influences that were not anticipated. In those cases, for example - length from shoulder point to last rib, where it was obvious that stance could have an effect, both sides were measured while the sheep was held firmly and the mean recorded.
Where stance could have no effect it was not considered necessary to measure and average measurements on each side. It is exceedingly doubtful whether any variation due to bilateral asymmetry would be recorded within the limits of accuracy obtained and a brief preliminary trial supported this view. There is no doubt that if such variations did exist they would be so small and so rare that the effect on the correlation coefficient would be negligible.

(4) Restlessness of Sheep.

The sheep used were, fortunately, accustomed to handling but they naturally became very restless when held in one position for long periods. This was not conducive to speed and accuracy of measurement but it was a difficulty that could only be met by patience; to a certain extent the instruments used enabled the investigator to meet slight movements on the animal's part.

(b) Measuring instruments (Fig. 1V).

After a little consideration three simple wooden instruments were evolved which proved quite satisfactory.

(a) (Fig 1V A). The majority of measurements were made with the simple dividers as illustrated; the most convenient size being with arms about fifteen inches long. A smaller divider was used for a few of the small measurements but this was not essential.

The arms of the dividers were held, one in each hand, with the index fingers lying along the points. In this way the wool could be parted, the reference points located with the index fingers and the points of the instrument held in position at the same time. This light simple instrument was particularly useful for restless sheep as small movements could be followed fairly easily.

(b) An adaptation of the above was necessary for measurements of the nature of diameters e.g. body depth and width. The instrument (Fig. 1V B) served this purpose and also had the advantages of the above in regard to simplicity and convenience.

(c) For large measurements such as body length and for perpendicular heights e.g. wither height, an instrument
(Fig IV C) was used - this consisted of a graduated rod with two arms at right angles, one being fixed and the other capable of sliding and rotating on the rod. There were two limitations in the use of this instrument which could not be overcome; it was by no means independent of restlessness and further the measurements for which it was used were liable to be affected by stance. It was found that restlessness generally increased the longer the sheep was held but that the stance was generally most unnatural at the beginning of the measuring process. In this case, restlessness was the lesser evil so that the use of this instrument was postponed until the sheep had relaxed.

Scales were attached to all three instruments so that the values could be read quickly; furthermore most recordings could be made while the instruments were being applied to the portions and were firmly held, so that possible errors due to twitching of the skin etc. were eliminated. Checks were also made at frequent intervals to ensure that the scales were giving true readings and had not suffered warping etc.

In order to eliminate the effect of the wool on the girth measurement a thin strong cord was used; the wool being parted so that the cord lay close to the skin.

An attempt was also made to measure various angles and slopes. With the possible exception of the angle of the hock, it was found quite impossible to measure angles and slopes directly with any accuracy. It will be obvious that angles would be particularly affected by comparatively slight movements and it is felt that it is not possible to place much reliance on them. The indirect method employed can be best explained by an illustration - slope of pelvis (see Fig V).

By subtracting the 'height to pin (BG₂) from the 'height to hook' (AG) we get the distance AC; the length of pelvis AB is known and the calculation of the angle of the slope is then a matter of simple trigonometry. The angle is ABC which equals the angle of slope of the pelvis from the horizontal (θ). The same principles may be applied to the slope of the shoulder etc.
From the above discussion, it will be apparent that a certain amount of error of measurement would be expected, owing mainly to the difficulty of locating reference points with accuracy. To some extent, of course, the difficulties were beyond the control of the investigator but, it is obvious that the personal skill acquired would be a very important factor. In order to obtain some measure of the error and also to develop skill, all measurements were repeated. When this was done it was found that the differences between the two recordings ranged from zero up to 10% in the case of a few difficult measurements and, in two or three instances, it was apparent that the measurements were quite unreliable.

It is obvious however, that the difference between these two recordings would not give a just measure of the error associated with the second series because of the skill developed by the time the latter were made; a certain number were therefore again repeated. Over 150 measurements were selected for repetition where the difference between the first and second recordings had been of a high order. It was felt that by so choosing the more difficult measurements, the error evaluated from them could be regarded with confidence as representing the maximum error that could be attributed to the second series.

The mean error of measurement calculated in this way was very nearly 4% of the second recordings - a figure which, under circumstances is gratifyingly low. Need hardly be mentioned that in all cases where repeat measurements were made, it was quite impossible for the investigator to remember previous readings.

An expression of the precise effect of this error on the correlation coefficient, apparently, would involve very complex mathematics and no method could be suggested by mathematicians whose assistance was sought. The general opinion was, however, that the effect of the error would probably not be great. Furthermore, according to Yule, the effect of error is to reduce

the correlation coefficient below its true value. This reduction will be more or less the same on all coefficients and will not, therefore, affect their value for purposes of comparison.

THE SIZE FACTOR

(a) Effect of the "size factor".

There have been references in the above paragraphs to the limitations of mathematical method in its application to biological data and a certain amount of doubt was felt, therefore, as to how far the use of complex and intricate mathematical method was justified. On the other hand, however, would not the very existence of such limitations emphasize the necessity for accuracy in the methods themselves? Furthermore, since this work is opening up a new field of research, it was felt that the time spent on the "size factor" problem was well advised.

It is no more than a truism that the size attained by the various parts of the body is in a large measure dependent on the size attained by the body as a whole; that is to say, a large sheep would have a longer head and longer pelvis, for example, than a small sheep.

In effect, this means that variation of general size amongst the sheep would superimpose a variation on a portion in addition to that which might be the independent property of that portion.

Since the nature of this superimposed variation is the same on all portions of the body, the "size factor" would of itself tend to produce a sympathetic variation between any two portions. If the portions were actually capable of independent variation the "size factor" would tend to obscure this fact while any real tendency to association between the portions would be accentuated.

The influence of the "size factor" on the correlation coefficient would therefore be -

(a) In cases of true zero correlation - to produce an apparent positive correlation
(b) In cases of true negative correlation - to produce a lower negative, a zero or even a slight positive correlation.
(c) In cases of true positive correlation - to produce an abnormally high coefficient.

On theoretical grounds, there is no doubt that the influence of general size is a factor that demands consideration but, on the other hand, there is considerable evidence to show that it has not been seriously considered, if at all, by many workers in allied subjects. The question arises as to whether the effect of the size factor was of sufficient magnitude to warrant elaborate devices for its elimination.

As stated above, the sheep measured were all mature ewes and consequently, the variation in size amongst them was not very great. It will be seen, however, that the variation among separate portions was also small, so that the relative effect of size variation might be considerable. It soon became obvious that the problem could not be solved by casual observation but that it would actually be necessary to devise means for eliminating the effect, before it would be possible to judge its influence.

(b) Methods of elimination.

(1) The most obvious method that would suggest itself is to express the measurements in terms relative to size, for example as percentages and this device has been employed in related work. However, on testing this method in an example, it was discovered that it contained a very serious flaw.

The correlation between humerus and radius calculated from actual measurements in inches was +0.15 whereas, when the values were expressed as percentages of wither height (using this as a size index) the correlation rose to +0.39. Since, as was pointed out above, the effect of the size factor on a positive correlation would be to produce an erroneously high figure, this result seemed inexplicable. The point was rather outside the field of statisticians to whom the matter was referred and only indirect information was available in textbooks. However, the idea of
simply abandoning the method with its flaw undiscovered did not appeal. In accordance with the conviction expressed in earlier sections - that a full understanding of statistical devices was prerequisite to their successful application - it was felt that the consideration of any matter likely to promote such understanding was more than justified.

Consideration in the present case made it possible to provide an explanation which seemed satisfactory.

It is apparent that the elimination of the size factor should decrease the variability of a portion, as it would reduce the range of variation without materially affecting the mean; in a sense, its elimination would cause the extreme values to shrink towards the mean. It was discovered, however, that in the above example the variability of the percentages was actually greater than that of the actual values in inches.

The coefficients of variability were:

- Humerus - from actual values in inches 3.95%
  "  " percentages 5.09%
- Radius  " actual values in inches 3.63%
  "  " percentages 3.66%

It is seen that the increase in variability was greater in the case of the humerus; the key to the solution of the problem was obtained when it was noted that the correlation coefficient between humerus and wither height was less than that between radius and wither height - the values being +0.13 and +0.46 respectively. A little consideration suggested that the 'percentage method' for eliminating the size factor involved an assumption which could not be made - namely, the assumption that the particular portion varies directly with size. Where the portion did not so vary the expression as percentages would tend to increase the variability. As we have seen above, this is precisely what took place; the effect being greater in the case of the humerus than in the case of the radius - that is, inversely as the degree of relationship between each of these portions and
wither height.

The percentage method would only be applicable where the portion considered varied directly with size - that is, exhibited perfect positive correlation with size; the obvious solution therefore, was to seek some method of eliminating the "size factor" which involved the actual correlation between the characters and size.

(11) The position is that there are two variables (any two portions of the sheep) whose true relationship is obscured by the influence of a third variable (general size). Mathematicians have devised a formula for the elimination of such a third variable which gives the "partial" or "net" correlation between two variables. Applied to the present work, partial correlation should express the mutual relationship between any two parts, independent of their common relationship to the general size of the animal.

The formula for "net" or "partial" correlation coefficient is:

\[ r_{12.3} = \frac{r_{12} - r_{13} \cdot r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}} \]

\[ r_{12.3} \] = the partial correlation between portions 1 and 2 with the effect of 3 eliminated.

\[ r_{12}, r_{13} \text{ etc} = \text{the gross correlations between portions 1 and 2, 1 and 3 etc.} \]

When this formula was applied to the example of humerus and radius used above, the partial correlation between the two portions was calculated to be +0.10 (gross = ±0.15) and from the above discussion it will be understood that such a reduction was the anticipated result of the elimination of the "size factor".

However, when a statistician was consulted with a view to obtaining confirmation of the value of this method, certain doubts were expressed. It appears that an American worker, Montgomery D. Anderson† has expressed doubts as to the reliability

Reference not available.
of the method when applied to factors which are concomi-
tantly related. It is considered that reliability is not obtained where the factor "partialled out" (i.e. size) is appreciably affected by either of the two factors between which partial correlation is sought. The point is obvious if we consider such an example as crop yield, weight of fertiliser per acre and rainfall. It is apparent that either fertiliser or rainfall could be "partialled out" whereas crop yield could not; in this case, for perfectly obvious reasons. Unfortunately no information could be obtained as to the exact reasons for Anderson's opinion and the question remains as to whether there are other reasons besides the obvious common-sense one that would apply to the case above/crop yield etc. Furthermore, it is somewhat debatable whether a small portion of the sheep could be regarded as "appreciably" affecting general size.

A study of statistical textbooks threw no light on the problem but it was felt that recourse to complex theoretical considerations was unnecessary and possibly even futile. Mathematical methods are not being used in this paper in order to prove the existence of skeletal relationships but rather as strictly mechanical devices for the expression of information that was apparent from a thorough understanding of the data. The opinion is held, therefore, that the validity of mathematical method in general and in this instance, partial correlation, must be judged, not by excursions into the intricacies of mathematical theory, but rather by careful consideration of the simple question - does it express the result to be anticipated from intelligent understanding of the data?

On this basis, it was concluded that the partial correlation method could be used with confidence.

It was at this stage of the work that a paper was accident-
ally discovered, by an American worker - F.B. Sumner who had...

+ Proceedings of the National Academy of Sciences, Vol. 9, No 11, November 1923.
calculated correlation coefficients between various portions of the deer mouse (Peromyscus). Unfortunately, he gave very little detail of the methods he employed and the cross references given were not obtainable in the libraries available. The question at issue in Sumner's paper was the extent to which the sizes of various portions were inherited independently but there are one or two points in his paper which have a bearing on the present work.

One interesting point was that Sumner criticised the work of Castle who had calculated correlation coefficients between parts of the rabbit, on the grounds that the latter had neglected to eliminate the "size factor". Sumney states that the extent to which the variation of a portion independent of general size factors is indicated by the percentage ratio of the "net" to the "gross" standard deviation. The latter is the ordinary standard deviation obtained from actual measurements and the "net" standard deviation is obtained from the "gross" by multiplying the latter by a factor $\sqrt{1 - r^2}$, where $r$ is the correlation coefficient between the portion and size. On applying this factor to the humerus of the sheep the "independent variability" of the portion was calculated to be 98.8% a result to be expected from the low correlation between humerus and wither height (using this as a size index). This factor of Sumner's has been mentioned as it was considered possible that it might be useful in later sections or extensions of this work.

Sumner also employed the partial correlation method but, unfortunately, he did not discuss its use and apparently did not question its validity. It was gratifying, however, to find the conclusions in regard to this method, supported by precedent provided by an American worker of repute.

(c) The size index.

The question remained as to the choice of a suitable measure of "general size". At first, it was felt that the best method would be to use the major measurement appropriate to the
particular portion under consideration, for example, wither height when considering cannon length or body length when considering length of loin. The obvious difficulty arose when considering the correlation between portions from distant parts of the body, e.g. cannon length and loin length and it became apparent that a single size index would need to be evolved.

It is obviously impossible to define "general size" as it is no more than a general impression to which all parts of the animal contribute. It was considered therefore, that a single major measurement such as wither height or body length would not be a good index of size but rather would it be necessary to use a composite index that would, as far as possible, represent all portions of the body. Furthermore, it was realised that any attempt to express general size in very precise terms would be absurd; actually, the elimination of the "size factor" amounts to little more than an arbitrary reduction of the correlation coefficient to an extent that depends on the estimated effect of size on the portions concerned.

The index, then, must be a general, "all-embracing" thing which reflects all those dimensions which contribute to the general impression of size; in effect, this would be obtained from a compound of the four major measurements - wither height, height to hook, girth and body length.

The gross correlation coefficients between these four measurements were not very large (considering that they were gross coefficients) and this gave more weight to the conclusion that all four be compounded in evolving the index.

The coefficients actually were:

<table>
<thead>
<tr>
<th>Measurement 1</th>
<th>Measurement 2</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wither height - Height to hook</td>
<td>+0.64 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>&quot;                         &quot;</td>
<td>Girth</td>
<td>+0.54 ± 0.11</td>
</tr>
<tr>
<td>&quot;                         &quot;</td>
<td>Body Length</td>
<td>+0.46 ± 0.12</td>
</tr>
<tr>
<td>Girth</td>
<td>Body Length</td>
<td>+0.49 ± 0.11</td>
</tr>
<tr>
<td>&quot;                         &quot;</td>
<td>Height to hook</td>
<td>+0.25 ± 0.14</td>
</tr>
<tr>
<td>Height to hook</td>
<td>Body Length</td>
<td>+0.44 ± 0.12</td>
</tr>
</tbody>
</table>
The "size index" was obtained by calculating the mean of these four major measurements. It was suggested that it might be advisable to employ a method that would give to each of the four measurements an equal "weight" in the index; in the simple arithmetic mean as used the largest measurement has, of course, the greatest "weight" in the index. On the other hand, however, the largest measurement contributes most towards "general size" and one would expect therefore that it should merit greatest "weight" in an index designed to represent general size.

It was considered that the validity of the "size index" would be tested by the correlation it exhibited with the four major measurements taken together i.e. by the method of multiple correlation. This multiple correlation was calculated to be +0.998. In this work this may be regarded as perfect positive correlation and it is considered that this indicates that the "size index" as calculated above fulfils the purpose for which it was designed; viz. to measure the composite effect of the four major measurements.

In other words the calculation of partial correlation coefficients with the "size index" held constant is equivalent to holding the four major measurements constant and so eliminating the effect of general size variation on the correlation coefficients - an effect, which will be seen from the results, to be very important.
SCATTER GRAPHS.

Scatter graphs are, at best, difficult to interpret but to some extent they indicate the extent of the correlation that exists and graphs have been plotted for different degrees of correlation. It is seen that where high correlation exists the points tend to lie in a diagonal band across the page while lack of correlation is indicated by an indiscriminate "scatter".

Regression Lines.

These may be drawn from the equation (referring to the intersection of the means):-

\[ d_x = r \frac{\sigma_x}{\sigma_y} d_y \]

\( d_x \) and \( d_y \) = deviations of \( x \) and \( y \) variables.

\( \sigma_x \) and \( \sigma_y \) = standard deviations of \( x \) and \( y \) variables.

\( r \) = correlation coefficient between \( x \) and \( y \).

\[ r \cdot \frac{\sigma_x}{\sigma_y} \] = the regression coefficient of \( x \) on \( y \).

If we substitute various values for \( d_y \) in the above equation we get values for \( d_x \) which lie in a straight line. The values of \( d_x \) so obtained, represent the average values of the deviations of \( x \) variables which will be associated with particular values of the deviations of \( y \) variables. In a similar way, the regression of \( y \) on \( x \) may be calculated simply by substituting \( y \) for \( x \) throughout the above equation.

This process is illustrated in graphs 1 and 11. The whole red line in graph 1 represents the regression of 'pelvis' on 'head length' and in graph 11 the regression of 'width eye-setting' on 'width between hooks' - the broken red lines indicate the reciprocal relation in each case.

It will be seen that the regression lines in graph 11 do not deviate greatly from the mean values of 'width eye setting' and of 'width between hooks'; in graph 1 where the correlation is greater the situation is very different. It appears then, that the position of the regression lines indicates the degree of correlation that exists.

At the present stage of this work, however, regression is
of little practical interest. The above brief mention of it has been made merely to show the further information obtainable from correlation data which may prove of value in extensions of this work.
SUMMARY OF PART II

(1) It was necessary to exercise great care in selecting the sheep on which to work. A brief discussion of the theoretical basis of correlation in its bearing on this problem revealed a somewhat complex situation but an endeavour was made to secure material which would contain only "true" correlations. The effect of sex and age was also considered and finally a 'sample' of twenty mature ewes was selected from the College Wool Experimental flock.

(2) Difficulties encountered in the actual measuring were to some extent overcome by the use of simple instruments. The development of a certain amount of skill in measuring reduced the error to a reasonable figure whose influence on the correlation coefficient was not serious.

(3) The results were expressed by Pearsonian correlation coefficients. An exact definition of the term "correlation" is difficult and it is necessary to emphasize that attributing very precise meanings to the coefficients is not justified.

(4) The most involved problem encountered was the elimination of the influence of general size variation on the coefficients. This was finally accomplished by using the "partial" or "net" correlation method and employing a composite size index.

(5) A few "scatter graphs" have been plotted to illustrate the nature of these graphs; examples of repression lines are also provided, but at present these are of little practical value.
Graph 1

Head Length and Pelvic Length

Gross r = +0.64
Graph 41

Eye-Setting

Width (Outside) eye-setting:
Width between hooks.
Gross r = 0.02.