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Brassinosteroids control gravitropism by changing cellulose orientation and mannan content in Arabidopsis hypocotyls

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Title:

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Running title:

Cell wall polymers control shoot gravitropism

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Highlight

Our data reveal new functions of cell wall polymers in gravitropic responses. Brassinosteroid-related changes in shoot gravitropism uncover that cellulose re-organization and mannan content influence shoot mechanical strength and bending.

Abstract

Shoot gravitropism is essential for plants to direct the growth of above-ground tissues towards the soil surface after germination. Brassinosteroids influence shoot gravitropism and we used this as a tool to untangle the function of cell wall polymers during etiolated shoot growth. The ability of etiolated Arabidopsis seedlings to grow upwards was suppressed in the presence of 24-epibrassinolide (EBL) but enhanced in the presence of Brassinazole (BRZ), an inhibitor of brassinosteroid biosynthesis. These effects were accompanied by changes in cell wall mechanics and composition. Cell wall biochemical analyses and confocal microscopy of the cellulose-specific pontamine S4B dye revealed that the EBL and BRZ treatments correlated with changes in cellulose fibre organization and mannan content. Indeed, a longitudinal re-orientation of cellulose fibres supported upright growth whereas the presence of mannans reduced gravitropic bending. The negative effect of mannans on gravitropic bending is a new function for this class of hemicelluloses, and provides insight into evolutionary adaptations by which aquatic ancestors of terrestrial plants colonized land.

Key words: Arabidopsis, brassinosteroids, cellulose, cell wall, creep, evolution, gravitropism, hypocotyl, mannan, shoot

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Introduction

All growing plant cells are encased in primary cell walls, which are strong to maintain cell and tissue integrity, yet extensible to allow for growth (Cosgrove, 2016). How these conflicting properties are achieved is uncertain because the exact architecture of primary cell walls is not well defined (Cosgrove, 2018). The traditional cell wall model, in which a load-bearing network of cellulose microfibrils, cross-linked by hemicelluloses, is embedded into an amorphous matrix of pectins and structural glycoproteins (Carpita and Gibeaut, 1993), has been substantially modified and improved (Cavalier *et al.*, 2008; Dick-Perez *et al.*, 2011). These modified models include a wall load-bearing capacity that is defined by either lateral cellulose/xyloglucan/cellulose contacts in restricted areas called "biomechanical hotspots" (Park and Cosgrove, 2012), and/or cellulose/pectin interactions (Phyo *et al.*, 2017*a*, *b*), and/or arabinogalactan proteins covalently linked with pectin and arabinoxylans (Tan *et al.*, 2013). At present, there is little consensus on the role of particular polysaccharides in cell walls, and there is therefore a need for experimental models that could help understand their functions and interactions. Negative gravitropism of young plant shoots, i.e. their upright growth against the gravity vector, can be used as one such model. Indeed, it is during this type of response that the conflicting properties of growing walls are especially prominent: their extensibility should be delicately balanced with the strength needed to maintain cell and tissue integrity, and to carry the weight of upright shoots in the field of gravity. Hence, the effects of even moderate experimentally imposed modifications of cell wall polymers could be revealed through changes in shoot gravitropism. Negative shoot gravitropism also involves gravitropic bending, an asymmetric shoot growth that restores its vertical position after inclination (Morita, 2010). Studying this response can provide insight into compression resistance or the contribution to plant organ flexibility of cell wall polymers, which is rarely addressed.

Brassinosteroids (BRs) constitute a class of phytohormones (Singh and Savaldi-Goldstein, 2015) that impact the negative gravitropism of Arabidopsis hypocotyls, which is largely supported by primary cell walls (Vandenbussche *et al.*, 2011). The gravitropic response of hypocotyls was suppressed by epibrassinolide (EBL), one of the most active natural BRs, while brassinazole (BRZ), a specific inhibitor of BR biosynthesis, stimulated it. These effects did not result from modified gravity perception, but were accompanied by changes in cell wall mechanics (Vandenbussche *et al.*, 2011). The biochemical basis of the BR-induced alterations in wall physical properties is, however, largely unknown. Comprehensive microarray data on BR effects on Arabidopsis plants revealed changes in many dozens of cell wall-related genes (Goda *et al.*, 2002; Song *et al.*, 2009; Sun *et al.*,

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2010; Yu *et al.*, 2011). Thus, the action of BRs, including that of EBL and BRZ, on Arabidopsis hypocotyl gravitropism could be mediated by a number of modifications at the cell wall level.

In the present work we combined high-resolution confocal microscopy, biochemical and biomechanical analyses of cell walls to study the mechanisms of EBL and BRZ action on the negative gravitropism of Arabidopsis hypocotyls.

Materials and methods

Plant material and growth conditions

Arabidopsis thaliana (L. Heynh.) wild type Columbia-0 and mutant plants were grown on half-strength Murashige and Skoog (MS) medium (pH 5.7) (Duchefa Biochemie) containing 0.68% (w/v) microagar (Duchefa Biochemie). Where indicated, the medium was supplemented with stock solutions of epibrassinolide (0.2 mM in methanol), brassinazole (2 mM in methanol) and oryzalin (500 µM in ethanol), such that their final concentrations were 100 nM, 1 µM and 250 nM, respectively. In each case the medium for control untreated plants was supplemented with corresponding volumes of methanol and/or ethanol.

Surface-sterilized seeds were sown aseptically on large (145×20 mm) round Petri plates (Greiner) containing the above-mentioned media. The seeds were stratified for 2 days at 4°C, and their synchronous germination was induced by exposure to fluorescent white light (150 µmol m^{-2} s^{-1}) for 6 h at 21°C. The moment of transfer to light, i.e. the beginning of induction, was taken as zero age for experimental plants. After the 6 h induction period the Petri plates were wrapped in two layers of thick aluminium foil and placed horizontally in an environmentally controlled growth room. Five-day-old etiolated plants grown at 21°C were used in experiments, unless specified otherwise.

Extensometry

Arabidopsis seedlings for creep tests were placed individually into 1.5 ml Eppendorf test tubes, frozen by plunging the closed tubes into liquid nitrogen, stored at -20°C and used for extensometry within two weeks after freezing. *In vitro* extension of frozen/thawed hypocoyls was measured with a custom-built constant load extensometer (Suslov and Verbelen, 2006). A 2- or 5-mm-long segment from the specified region of a hypocotyl was secured between clamps of the extensometer and preincubated in a buffer (20 mM MES-KOH, pH 6.0) in the relaxed state for 2 min. Then, its time-dependent extension (creep)

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was measured in the same buffer under 625 mg or 750 mg loads for 15 min. The relative creep rate was calculated as described in Vandenbussche *et al.* (2011).

Cell wall biochemical analyses

Approximately 300 of 5-day-old seedlings per sample were rapidly harvested to a large volume of 70% EtOH, after which their seed coats were removed and discarded. The resulting plant material was transferred to a 2 ml Eppendorf test tube, 1.5 ml of 70% EtOH was added, followed by centrifugation at 10,000 rpm for 5 min discarding the supernatant. One ml of acetone was added to the resulting pellet, followed by centrifugation at 10,000 rpm for 5 min. The supernatant was discarded, and the residue was air-dried overnight. The resulting dry material was ball-milled (Retsch) for 1 min. One ml of EtOH was added to the residue, followed by centrifugation at 21,000 g for 10 min discarding the supernatant. Then 1 ml of MeOH:chloroform (1:1) mixture was added, followed by centrifugation at 21,000 g for 10 min, discarding the supernatant and air-drying the pellet. The resulting powdered cell wall pellet was weighed and transferred to a clean screw-capped Eppendorf test tube. *Myo*-Inositol (30 μl of 1 mg ml^{-1} solution in water) was added to the test tube as internal standard. Then 250 μl of 2M TFA was added, followed by incubation at 121°C for 1 h to hydrolyze cell wall polysaccharides. The tube was rapidly cooled on ice, 300 μl of 2-propanol was added and evaporated at 40°C, and the step with 2-propanol was repeated two more times. After this 250 μl of H_2O was added, and the tube was vortexed, sonicated for 10 min and centrifuged at 21,000 g for 10 min. One part of the resulting supernatant was taken for uronic acids quantification (2 × 50 μl), and the other portion (100 μl) was dried and used for assaying cell wall monosaccharides, while the pellet was processed for crystalline cellulose quantification. Subsequent cell wall biochemical analyses were carried out as described in Sanchez-Rodriguez *et al.* (2012). Uronic acids were colorimetrically measured using 2-hydroxydiphenyl as reagent (Vilím, 1985) with galacturonic acid as standard (Filisetti-Cozzi and Carpita, 1991). Cell wall monosaccharides were assayed as alditol acetate derivatives (Neumetzler, 2010) using a modified protocol from Albersheim et al. (1967) by gas chromatography performed on an Agilent 6890N GC system coupled with an Agilent 5973N mass selective detector. Crystalline cellulose was determined by Seaman hydrolysis (Selvendran and O'Neill, 1987) using Glc equivalents as standard, where the cellulosic Glc content was determined with the anthrone assay (Dische, 1962).

Microscopy

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Cellulose macrofibrils were visualized in cell walls with Pontamine Fast Scarlet 4B (S4B) dye (Anderson *et al*., 2010). In some experiments, living seedlings were stained in 0.2% (w/v) S4B for 30 min, which revealed macrofibrils only in the upper growing parts of hypocotyls. To provide the dye penetration to the cell walls at the base of hypocotyls, plants were extracted under mild conditions by sequential washes with EtOH:100% acetic acid (7:1, v/v) for 1 h; 100% EtOH for 15 min; 50% EtOH in H_2O for 15 min; and 1M KOH in H_2O for 30 min. All washing steps were carried out on a rotator. Experimental samples were stored in 1M KOH at 4°C before analysis or used immediately after the last alkaline wash for cellulose visualization. The samples were rinsed in H_2O before staining to remove residual KOH, after which 0.2% (w/v) S4B was added for 30 min. Then they were rapidly rinsed with a large volume of H_2O to remove excessive dye and observed under a spinning disc confocal microscope or super-resolution Airyscan confocal microscope (LSM880). The equipment for spinning disc confocal microscopy included a Nikon Ti-E inverted confocal microscope equipped with a CSU-X1 spinning disc head (Yokogawa, Japan), a 100x CFI Apo oil immersion TIRF objective (NA 1.49, Nikon, Japan), an evolve charge-coupled device camera (Photometrics Technology, USA), and a 1.2x lens between the spinning disc and camera. S4B was excited using a 561 nm laser (similar to Anderson *et al.*, 2010). Image acquisitions were performed using Metamorph software (Molecular Devices, USA) version 7.5. High-resolution imaging of cellulose macrofibrils was performed on a Zeiss LSM880 microscope equipped with an AiryScan Unit (Huff, 2015). S4B was excited using a 514 nm Argon Laser through a 458/514 MBS and a 63x Plan-Apochromat oil objective with a numeric aperture of 1.4. The 514 laser was used as 535 nm was indicated as an optimal S4B excitation wavelength (Anderson *et al.*, 2010) and as these settings provided good images for analyses. Emission was detected using the 32 GaAsP PMT array AiryScan unit. For each 8-bit image, a Z-stack consisting of 2-5 images with a 1 µm step-size, an image size of 1672x1672 pixels, and with 1.26 µs pixel dwell time was recorded. The recordings were deconvoluted using the Zeiss ZEN software at highest possible resolution.

Epidermal cell images at the base of hypocotyls were captured with a Leica DM 4000 light microscope equipped with a 1.3 megapixel CCD camera using a dark field mode, under a HCX PL FLUOTAR 20x/0.40 CORR objective. Cell lengths were then measured on digital images using a segmented line tool in ImageJ 1.49b software.

Time lapse photography by infrared imaging

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For gravitropic reorientation assays, plants were grown in infrared light (930 nm) on vertical plates containing media. Plates with three-day-old seedlings were rotated 90° (time point 0). Subsequently, the seedlings were imaged using infrared enabled cameras (Vandenbussche *et al.*, 2010). Images were analysed using the angle tool in ImageJ.

Results

Brassinosteroids strongly affect etiolated shoot gravitropism in Arabidopsis

To corroborate that the gravitropic response of etiolated Arabidopsis seedlings was altered upon changes in BR signaling (Vandenbussche *et al.*, 2011), we grew seedlings on horizontal Petri plates in the presence of exogenous EBL or BRZ and counted upright hypocotyls (Fig. 1). Plants grown on one-half strength MS media had 40-80% of upright hypocotyls (Fig. 1A). Media supplemented with EBL (100 nM) resulted in a decreased proportion of standing hypocotyls to 0-5% (Fig. 1B), while media containing BRZ (1 μM) increased it to 90-100% (Fig. 1C). These observations were consistent essentially from the moment of germination and demonstrate that BRs negatively affect shoot gravitropism.

Brassinosteroids influence etiolated shoot gravitropism via changes in cell wall mechanics

The influence of EBL on gravitropism (Fig. 1B) was hypothesized to emanate from cell wall weakening and thus an inability to keep hypocotyls upright in the field of gravity (Vandenbussche *et al.*, 2011). EBL had no effect on gravitropic bending in Arabidopsis plants grown on vertical Petri plates and gravistimulated by a 90 degrees clockwise rotation of the plates (see Fig. 4 in Vandenbussche *et al.*, 2011). In contrast, BRZ increased both the percentage of upright hypocotyls and their gravitropic bending, but its effect on cell wall mechanics remains unclear (Vandenbussche *et al.*, 2011).

We used the creep (constant-load) method to assess the biomechanical control of shoot gravitropism. Whenever hypocotyl length afforded, we stretched their basal regions, carrying the main part of the organ weight in the field of gravity, as well as their apical growing regions that are responsible for gravitropic bending (Fig. 2A). The scheme in Figure 2A illustrates the established age-dependent shift of growth zones in etiolated Arabidopsis hypocotyls; from the base towards cotyledons (Gendreau *et al.*, 1997; Bastien *et al.*, 2016). As BRZ greatly inhibited etiolated hypocotyl elongation (Fig. 1A, C), we compared cell wall creep in BRZ-grown plants with their age-matched 6-day-old untreated counterparts, as well as with 3-day-old untreated “genetic controls”, which are approximately the same length as the 6-day-old BRZ-grown plants (Fig. 2B). BRZ significantly decreased creep rates compared with both controls, which is consistent with

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cell wall strengthening. Thus, the inhibition of BR biosynthesis leads to an increase in negative gravitropism of hypocotyls, not only through the stimulation of gravitropic bending (Fig. 4 in Vandenbussche *et al.*, 2011), but also by cell wall strengthening that confers support to hypocotyls in the field of gravity (Fig. 2B). The creep rate analyses in EBL-grown plants revealed that the weakening of cell walls was mostly restricted to the basal nonexpanding hypocotyl zones (Fig. 2C-E). Hence, EBL may affect gravitropism (Fig. 1B) by interfering with the cell wall strengthening, which takes place in the basal regions of etiolated hypocotyls (Fig. 2D, E) where cell expansion has already ceased (Gendreau *et al.*, 1997).

Changes in cell wall biochemistry underpin the effects of BRs on gravitropism

To investigate how the cell walls are altered during BR exposure, thereby influencing cell wall mechanics and hypocotyl gravitropism, we performed standard cell wall biochemical analyses (Fig. 3). The content of uronic acids, which are the principal constituents of pectins, was unaffected by the EBL or BRZ treatments (Fig. 3A). By contrast, crystalline cellulose levels were significantly decreased in BRZ treated seedlings as compared with the untreated control, while EBL had no effect on this polymer level (Fig. 3B). As for monosaccharide composition of cell wall matrix polymers, both EBL and BRZ treatments significantly increased rhamnose content (Fig. 3C). In addition, BRZ treatment decreased mannose and increased glucose in cell wall matrix polysaccharides (Fig. 3C). Changes in rhamnose are likely due to the metabolism of rhamnogalacturonan I, which is the main source of this monosaccharide in primary cell walls. As EBL and BRZ caused opposite effects on gravitropism (Fig. 1B, C) but induced very similar increases in rhamnose (Fig. 3C), we argued that it is unlikely that this sugar is underpinning our observed phenotype. We did therefore not consider the rhamnose change in further details. Mannose is the principal constituent of cell wall mannans and the BRZ-induced decrease of mannose could therefore be caused by partial mannan depletion in the seedling cell walls. The BRZ-induced increase in glucose was not accompanied by any xylose accumulation (Fig. 3C) indicating that it is not associated with xyloglucans. On the other hand, the increase in glucose correlated with a decrease in crystalline cellulose (Fig. 3B). The inverse relationship between crystalline cellulose (Fig. 3B) and glucose (Fig. 3C) could be explained by a larger amorphous component of cellulose microfibrils, which is likely to be sensitive to TFA hydrolysis, perhaps explaining the apparent increase in glucose content in BRZ treated seedlings (Fig. 3C).

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EBL-induced suppression of etiolated hypocotyl gravitropism is related to cellulose arrangement

Rather unexpectedly, the strong effect of EBL on cell wall mechanics (Fig. 2C-E) was not associated with prominent changes in cell wall biochemical composition (Fig. 3). Nevertheless, not only the levels of certain cell wall polymers, but also their orientations and interactions in the wall affect cell wall mechanics, with implications both on cellular strength and expansion. This is especially true for cellulose, the strongest cell wall component (Suslov and Verbelen, 2006; Suslov *et al.*, 2009). To examine the orientation of cellulose in outer epidermal cell walls of hypocotyls from control and EBL-grown plants we used the specific fluorescent dye Pontamine Fast Scarlet 4B (S4B) (Anderson *et al.*, 2009). We imaged the dye-associated cellulose fibers using spinning-disc or high-resolution Airyscan confocal microscopy. With these set-ups we could reveal distinct cellulose macrofibril orientations. To improve the penetration of the dye and visualization of the cellulose fibers along the whole hypocotyl length we performed a mild extraction of cell walls. Without this treatment the cellulose fibers were not well discerned in the basal parts of living hypocotyls. Nevertheless, we made sure that living and extracted seedlings displayed similar cellulose arrangements in the upper growing region of their hypocotyls. In this part of control seedlings transverse buckling was frequently observed in the innermost wall layer. This phenomenon occurred in approximately 50% of both living and extracted control hypocotyls, and complicated cellulose macrofibril visualization on the inner wall face. In the remaining samples, i.e. in which we did not observe the buckling, cellulose macrofibrils were clearly transverse in the innermost wall layer and longitudinal in the outermost layer (Supplementary Video S1; Fig. 4A; Table 1). In the basal non-growing region of control hypocotyls, we observed slight or no buckling of the wall inner surface. These walls contained less transverse macrofibrils in the innermost layer and more thick longitudinal macrofibrils in the outermost layer compared with the upper growing region of hypocotyls (Supplementary Video S2; Fig. 4D; Table 1). In the upper region of approximately 50% of hypocotyls from EBL-grown plants, we observed irregular buckling in the innermost wall. In the samples without buckling, cellulose macrofibrils were more obliquely oriented (Fig. 4B), or decreased in relative abundance, compared with the untreated control. EBL did not influence longitudinal macrofibrils in the outermost wall layer in the growing zone of hypocotyls (Supplementary Video S3). The most dramatic EBL effect on cellulose orientation was found in the basal region of hypocotyls where it essentially eliminated longitudinal macrofibrils, such that the remaining ones were apparently thinner and had either oblique or random orientation (Fig. 4E; Supplementary

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Video S4; Table 1). This reduction in longitudinal macrofibrils at the hypocotyl base was a unique effect observed only in EBL-treated seedlings (Table 1; Fig. 4).

To confirm that the EBL-induced suppression of gravitropism was associated with macrofibril disorganization, we attempted to "randomize" cellulose orientation in the cell walls and then see how this affected the percentage of standing hypocotyls (Fig. 5). For this purpose, Arabidopsis seedlings were grown in the presence of 250 nM oryzalin, which partially disassembles cortical microtubules, thereby affecting the direction of cellulose microfibril deposition in the cell wall (Paredez *et al.*, 2006). This low concentration of oryzalin induced similar changes in cellulose arrangement as those observed with EBL in the upper part of hypocotyls (compare Supplementary Video S5 with Supplementary Video S3; Fig. 4B, G; Table 1), and significantly decreased the percentage of standing hypocotyls (Fig. 5). Thus, intact cellulose orientation is important for the negative gravitropism of hypocotyls, and the mechanism of EBL action on gravitropism may be based on changes in cellulose arrangement. However, the effect of oryzalin on the percentage of upright hypocotyls (Fig. 5) was weaker than that of EBL (Fig. 1B). This difference can be explained by the inability of oryzalin to alter longitudinal cellulose macrofibrils in the basal region of hypocotyls, in contrast to the effect of EBL (compare Supplementary Video S6 with Supplementary Video S4; and Fig. 4E with Fig. 4I; Table 1). These longitudinal macrofibrils accumulated in the outermost wall layer where they appear to contribute to the mechanical strength and upright growth of hypocotyls. Their reduced presence in EBL-treated seedlings (Fig. 4E, Supplementary Video S4) correlated with weaker walls at the base of hypocotyls (Fig. 2D, E).

BRZ increases the negative gravitropism of etiolated hypocotyls via several different mechanisms

Interestingly, the promoting effect of BRZ on gravitropism was independent of oryzalin treatment (250 nM) (Fig. 5). These data suggest that BRZ either regulates gravitropism somewhat independently of cellulose orientation, and/or antagonizes the oryzalin-induced macrofibril randomization. Our microscopic observations supported the first option, because we observed less ordered cellulose orientations in the upper parts of seedlings treated with oryzalin and BRZ (Fig. 4C, H; Supplementary Videos S7, S8; Table 1). At the same time the cellulose arrangement in the basal hypocotyl part was essentially similar in the untreated controls and seedlings grown in the presence of BRZ, oryzalin, and BRZ plus oryzalin (Fig. 4D, F, I, J; Supplementary Videos S2, S6, S9, S10; Table 1).

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Our cell wall biochemical data suggest that BRZ may affect gravitropism in a cellulose-independent manner. One such mechanism might be mediated by reducing the mannan content (Fig. 3C). To assess whether a decrease in mannan content affected negative gravitropism we studied triple *csla2csla3csla9* mutant plants lacking detectable glucomannans (Goubet *et al.*, 2009). The triple mutation did not influence the percentage of standing hypocotyls (Supplementary Fig. S1). However, by analogy with BRZ, the mutants displayed significantly accelerated gravitropic bending in reorientation assays with plants grown on vertical Petri plates (Fig. 6). Interestingly, the coefficient of BRZ stimulation of gravitropic bending was reduced in the background of *csla2csla3csla9* compared with Col-0 (Fig. 6, Table 2). The above findings show that the decreased mannan content (Fig. 3C) accounts – at least in part - for the BRZ-induced increase in gravitropic bending.

Plant cell expansion is known to be induced by cell wall loosening (Cosgrove, 2016; Ivakov *et al.*, 2017). Cell growth is slow and uniform along the length of young etiolated hypocotyls that have just emerged from germinating seeds (Refrégier *et al.*, 2004). A wave of rapid cell expansion starts at the base of hypocotyls at about 48 h post induction, after which it spreads acropetally towards cotyledons (Gendreau *et al.*, 1997; Bastien *et al.*, 2016). Hence, cell wall loosening is highly induced in the basal region of hypocotyls carrying their whole weight, which can interfere with keeping the upright position of this organ in the field of gravity. As the effect of BRZ on gravitropism is seen from the moment of hypocotyl emergence from seeds, it can result, among other things, from the particular distribution of cell expansion and, hence, cell wall loosening in very young hypocotyls. To test this option, cell length was measured in epidermal cell files at two developmental stages (Fig. 7A), allowing growth rate calculation for individual cells along hypocotyls (Fig. 7B). Only lower halves of epidermal cell files comprising ten cells were considered. These are the regions where the rapid growth is first initiated in hypocotyls (Gendreau *et al.*, 1997). Cell length was measured at 55 h post induction, the time point corresponding to the earliest phase of rapid growth in hypocotyls (Pelletier *et al.*, 2010), and at 72 h post induction, when maximal growth rate is attained (Gendreau *et al.*, 1997). Epidermal cell length was significantly lower in hypocotyls of BRZ-treated vs. control plants for all cells with the exception of the first cell at 55 h illustrating severe growth inhibition due to a decrease in BRs biosynthesis (Fig. 7A). The rate of cell expansion was also significantly lower for the majority of cells in BRZ-treated vs. control plants suggesting that the wall loosening was inhibited in the former (Fig. 7B). Interestingly, two peaks of growth inhibition were observed in BRZ-treated seedlings: at the base of hypocotyls (cells one and three)

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and in their most apical zone examined (cells nine and ten) (Fig. 7B). Thus, the wave of rapid growth is initiated in a higher region of hypocotyls and spreads acropetally slower in BRZ-treated vs. control plants. Overall, the above data suggest that cell wall loosening is inhibited more strongly at the base of hypocotyls, i.e. in the region responsible for carrying the seedling weight in the field of gravity. This inhibition can be another mechanism by which BRZ increases the percentage of standing hypocotyls.

Discussion

The two prerequisites for normal negative gravitropism in young shoots, mechanical strength and gravitropic bending, are based on distinct physiological mechanisms, which are linked through the cell wall characteristics. The mechanical strength of young shoots is defined by turgor and their primary cell walls (Shah *et al.*, 2017). This is well illustrated by wilting, a loss of turgor, when young shoots do not keep their upright position and lie down on the ground. Turgor depends on the transmembrane concentration gradient of osmotically active compounds, the hydraulic conductance and wall yielding properties (Ray *et al.*, 1972). It is said to be in dynamic balance between wall yielding, which tends to decrease turgor, and water uptake, which tends to increase turgor pressure (Cosgrove, 1986). Hence, changes in the wall properties, reflected by increasing (Fig. 2C-E) and decreasing (Fig. 2B) creep rates in the presence of EBL and BRZ, respectively, will contribute to lower and higher turgor values, which underpin the BR effect on gravitropism (Fig. 1). However, we cannot exclude that these effects are partially mediated by osmotic adjustments also influencing turgor pressure, which was not addressed here. Similarly, the selective BRZ-induced growth inhibition at the hypocotyl base (Fig. 7B), presumably mediated by decreased cell wall yielding, could elevate turgor, thereby maintaining their upright position.

Gravitropic bending results from asymmetric cell expansion on the opposite flanks of gravistimulated organs (Millner *et al.*, 2007). In young shoots put horizontally this response originates from simultaneous growth inhibition and stimulation on their upper and lower flanks, respectively (Bagshaw and Cleland, 1990; Cosgrove, 1990a; Ikushima *et al.*, 2008). As in the case of cell expansion in vertical plant organs (Cosgrove, 2018), the growth responses during gravitropic bending are controlled by cell wall yielding properties (Bagshaw and Cleland, 1990; Cosgrove, 1990b; Edelmann and Samajova, 1999; Ikushima *et al.*, 2008). Cell wall extensibility always decreases on the upper sides and sometimes increases on the lower sides of gravistimulated shoots, such that the overall cell wall loosening or tightening prevails depending on the species (Edelmann, 1997) and/or the

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phase of gravitropic bending (Bagshaw and Cleland, 1990). However, this prevalent overall loosening and tightening will not affect the percentage of standing 5- and 6-day old Arabidopsis hypocotyls in which the zone of gravitropic bending is physically separated from the basal zone that is mostly responsible for the mechanical strength needed for shoot gravitropism (Fig. 2A).

There is another scenario in which gravitropic bending can contribute to the percentage of standing young shoots. Seeds of plant species, which have no special adaptive mechanisms for oriented dispersal on the soil surface, will land on it with random orientations. Those seeds in which embryonal shoots are directed upwards in/on the soil will have a higher chance to produce standing hypocotyls as this seed orientation minimizes any contacts of growing shoots with the potentially adhesive soil surface. The embryonal shoots of seeds oriented upside down in/on the soil will have to efficiently bend to attain the correct upward orientation. It is hypothesized that the more rapid the shoot bends, the lower its contacts with the adhesive surrounding soil, leading to a higher percentage of standing shoots. In general, rapid growth is nonoptimal for negative gravitropism in shoots because it decreases their mechanical strength. Hence, cell extension should be very delicately controlled at the base and during bending of young shoots to support their negative gravitropism.

Cellulose is the strongest cell wall component. The requirement of high wall mechanical strength for shoot gravitropism suggests that the arrangement of microfibrils could affect this process. The modulus of individual cellulose microfibrils ranges from 0.7 to 3.5 GPa (Chanliaud *et al.*, 2002), which is about 100-fold greater than the tensile modulus of primary cell walls (Ryden *et al.*, 2003). Due to this fact, cellulose microfibrils never extend axially under physiological conditions, instead they separate from each other, bend, slide past each other and reorient in the direction of strain during growth, or under external forces, resulting in cell wall deformations (Preston, 1982; Refrégier *et al.*, 2004; Zhang *et al.*, 2017). The cellulose mobility depends on microfibril-microfibril and microfibril-matrix interactions, proteinaceous cell wall loosening/tightening factors (Chanliaud *et al.*, 2002; Chanliaud *et al.*, 2004; Zhang *et al.*, 2017) and cellulose orientation that is defined by cortical microtubules (Paredez *et al.*, 2006; Bringmann *et al.*, 2012). BRs affect many processes linked with cellulose. They transcriptionally regulate the majority of *CESA* genes encoding catalytic subunits of cellulose synthase complexes through the involvement of the BR-activated transcription factor BES1 (Xie *et al.*, 2011). Additionally, BRs influence cellulose synthesis posttranslationally: the negative regulator of BR signaling, BRASSINOSTEROID INSENSITIVE2 (BIN2), can phosphorylate one of the cellulose

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synthase subunits that leads to impaired cellulose synthesis (Sanchez-Rodriguez *et al.*, 2017). These mechanisms can be the cause for the BRZ-induced decrease in cellulose content (Fig. 3B). BRs may also change microfibril orientation as they influence cortical microtubule organization (Gupta *et al.*, 2012), possibly via BIN2 (Liu *et al.*, 2018). Hence, the EBL-induced formation of oblique cellulose macrofibrils in the inner wall layer adjacent to the plasma membrane (Fig. 4B, E; Table 1; Supplementary Movies S3 and S4) may result from cortical microtubule reorientations.

We observed two additional cellulose-related effects of BRs. First, the BRZ-induced decrease in crystalline cellulose and increase in the TFA-released glucose, without increase in xylose (Fig. 3B, C), can be interpreted as a decrease in the cellulose crystallinity. Similar observations were made in *isoxaben resistant* (*ixr*) mutants (DeBolt *et al.*, 2013). BRZ could thus generate cellulose microfibrils with reduced crystallinity and more exposed glucan chains. This might provide a larger surface area, and thus additional sites, for noncovalent interactions with adjacent microfibrils and matrix polysaccharides. The 'rough' surface of such microfibrils could also provide a better access for enzymes forming covalent cross-links between cell wall components. A good candidate for this role is AtXTH3 that catalyses cellulose-cellulose, cellulose-xyloglucan and xyloglucan-xyloglucan transglycosylation (Shinohara *et al.*, 2017). All these additional noncovalent and covalent interactions could explain the increased wall mechanical strength observed with BRZ treatment (Fig. 2B) that contributes to the negative gravitropism of hypocotyls (Fig. 1C).

The second cellulose-related effect of BRs is the EBL-induced macrofibril disorganization at the base of hypocotyls (Fig. 4E; Supplementary Video S4). The overall arrangement of macrofibrils along Arabidopsis hypocotyls is consistent with the classical multinet growth theory, according to which cellulose is deposited transversely next to the plasma membrane, followed by a passive microfibril displacement into deeper wall layers and their axial reorientation, i.e. parallel to the direction of maximal growth (Roelofsen, 1958; Preston, 1982; Refrégier *et al.*, 2004). Transverse and longitudinal macrofibrils were observed in the inner and the outer wall layer, respectively, both in the upper and the lower half of control hypocotyls (Supplementary Videos S1 and S2). Longitudinal macrofibrils were clearly more prevalent in the lower fully elongated region compared with the upper elongating region of hypocotyls, because in the former zone they had more time for the passive reorientation in the direction of growth. Cellulose in the upper half of EBL-treated hypocotyls also demonstrated a multinet-like axial reorientation from rare oblique macrofibrils in the inner wall layer to thick abundant longitudinal macrofibrils in its outer

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layer (Supplementary Video S3). The lower halves of these hypocotyls contained relatively abundant oblique macrofibrils with few thin longitudinal macrofibrils on the outer wall face (Supplementary Video S4). Keeping in mind that epidermal cells at the base of hypocotyls are at a later developmental stage than those at the apex (Gendreau *et al.*, 1997; Bastien *et al.*, 2016), it means that the majority of longitudinal macrofibrils in the outer wall layer are post-synthetically re-oriented to produce oblique ones in fully elongated cells. A force that drives such re-orientation must be very high. The most likely candidate for this role is a change in the wall hydration generating forces that can rearrange cellulose microfibrils (Huang *et al.*, 2018). In line with this hypothesis BRs were shown to induce a rapid wall swelling (Caesar *et al.*, 2011). Irrespectively of the mechanisms involved, the elimination and thinning of longitudinal cellulose macrofibrils observed at the base of hypocotyls from EBL-grown plants could decrease their resistance to bending, such that they can easily curve under their own weight and fall on the agar surface (Fig. 1B), which would decrease the negative gravitropism of hypocotyls.

Mannans are minor hemicelluloses of primary cell walls in angiosperms. Their backbones are either composed of (1→4)-β-D-mannose residues only (pure mannan), or contain (1→4)-β-linked D-glucose and D-mannose residues distributed along the chain in a non-regular fashion (glucomannan). Both polysaccharides can have (1→6)-α-D-galactose substitutions on their backbones, in which case they are referred to as galactomannans and galactoglucomannans, respectively (Schröder *et al.*, 2009). Mannans are often utilized as storage polysacharides in seeds, bulbs and tubers. They also seem to play a structural role in the secondary cell walls of gymnosperms, where mannans are abundant (Hosoo *et al.*, 2002), and such a role was inferred from the experiments on cell wall analogues (Whitney *et al.*, 1998). However, doubts have been cast on the structural functions of mannans in primary cell walls based on the phenotype of Arabidopsis triple mutant *csla2csla3csla9*. Being deficient in mannan biosynthesis and containing no detectable glucomannans, the mutant seedlings were phenotypically indistinguishable from their wild type counterparts (Goubet *et al.*, 2009). Our findings that BRZ decreases the content of mannose in cell wall matrix polysaccharides (Fig. 3C), while increasing the gravitropic bending of hypocotyls (Vandenbussche *et al.*, 2011; Fig. 6), and that the triple mutation *csla2csla3csla9* increases the gravitropic curvature (Fig. 6) with no effect on the percentage of upright hypocotyls (Supplementary Fig. S1) show that mannans have a negative effect on gravitropic bending. This role in shoot gravitropism is a new function for mannan polysaccharides. Interestingly, our data are consistent with the fact that gravistimulation of wild type Arabidopsis seedlings is accompanied by a strong

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downregulation of one *CSLA* gene responsible for mannan biosynthesis (Millar and Kiss, 2013). Additionally, the level of galactoglucomannans was decreased by about 50% in maize stem pulvini as a result of gravistimulation (Zhang *et al.*, 2011). The negative influence of mannans on shoot gravitropism is interesting from an evolutionary perspective. Aquatic ancestors of terrestrial plants used buoyancy to support their bodies (Hejnowicz, 1997). Hence, the mechanisms of shoot gravitropism evolved when plants began to thrive on land instead of in an aquatic environment. According to recent data, terrestrial plants originated from the advanced charophycean green algae (CGA) of the order Zygnematales (Wickett *et al.*, 2014). CGA cell walls contain mannans and xylans as principal hemicelluloses (Popper and Tuohy, 2010), whereas xyloglucans emerge in some members of this group including Zygnematales (Sørensen *et al.*, 2010). The evolution of terrestrial plants involves a gradual increase in the xyloglucan content of primary cell walls and an opposite trend for mannans (Popper, 2008). These data suggest that the emergence of xyloglucans in CGA might have formed a basis for subsequent land colonization. At the same time, the properties of mannans may not be well suited for land habitats. In this evolutionary context it is important to find out why mannans interfere with gravitropic bending. The precise mechanism of the effect is unknown, but we consider three hypotheses:

1) Glucomannans have less regularly organized backbones than xyloglucans (Schroder *et al.*, 2009) making them insufficiently flexible alone or in a complex with different cell wall components to support the rapid formation of gravitropic bending.

2) Mannans could interfere with the activities of xyloglucan endotransglucosylase/hydrolases (XTHs) that seem to participate in the mechanism of gravitropic bending (Zhang *et al.*, 2011; Hu *et al.*, 2013). XTHs were shown to use non-xyloglucan polysaccharides as donor substrates, although much less efficiently than xyloglucans (Maris *et al.*, 2011; Shinohara et al., 2017). If XTHs have some affinity for mannans, their presence could decrease the enzyme's action on xyloglucans in a competitive manner, thereby impairing the function of specific XTHs during gravitropism.

3) Changes in mannan synthesis can affect gravitropic bending by modulating the level of reactive oxygen species (ROS). This scenario is possible because GDP-mannose is a common precursor in the biosynthesis of mannans and ascorbate (Sawake et al., 2015). Accordingly, the downregulation of *CSLA* gene expression by gravistimulation (Millar and Kiss, 2013), BRZ or different cues will increase the GDP-mannose pool available for ascorbate biosynthesis. The resulting increase in ascorbate, a strong

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antioxidant, will modulate ROS levels, which are important for gravitropic responses (Joo *et al.*, 2001; Krieger *et al.*, 2016; Singh *et al.*, 2017; Zhou *et al.*, 2018).

These mechanisms are not mutually exclusive. Studying their contribution to shoot gravitropism will shed light to the role of mannans in cell wall architecture. This could also improve our understanding of key cell wall modifications that allowed successful land colonization by aquatic ancestors of terrestrial plants.

In summary, by studying the effects of brassinosteroids on shoot gravitropism at the cell wall level we have revealed that mannans interfere with gravitropic bending of Arabidopsis hypocotyls, which is a new function for these minor hemicelluloses of primary cell walls. Additionally, both the pattern of cellulose macrofibrils and slow cell expansion at the base of hypocotyls are important for their upright growth during negative gravitropism. Thus, the modulation of brassinosteroid content in shoot gravitropism studies provides a convenient system for revealing the functions of polymers in primary cell walls.

Supplementary data

Supplementary data are available at *JXB* online.

Figure S1. The percentage of standing hypocotyls in *Col-0* and *csla2csla3csla9* Arabidopsis seedlings.

Video S1. Cellulose macrofibrils in the upper region of hypocotyls from control seedlings. In this and following videos cellulose arrangement is represented in the order from the innermost to the outermost layer of the outer epidermal cell wall.

Video S2. Cellulose macrofibrils in the basal region of hypocotyls from control seedlings.

Video S3. Cellulose macrofibrils in the upper region of hypocotyls from EBL-grown seedlings.

Video S4. Cellulose macrofibrils in the basal region of hypocotyls from EBL-grown seedlings.

Video S5. Cellulose macrofibrils in the upper region of hypocotyls from oryzalin-grown seedlings.

Video S6. Cellulose macrofibrils in the basal region of hypocotyls from oryzalin-grown seedlings.

Video S7. Cellulose macrofibrils in the upper region of hypocotyls from BRZ-grown seedlings.

Video S8. Cellulose macrofibrils in the upper region of hypocotyls from seedlings grown with BRZ plus oryzalin.

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Video S9. Cellulose macrofibrils in the basal region of hypocotyls from BRZ-grown seedlings.

Video S10. Cellulose macrofibrils in the basal region of hypocotyls from seedlings grown with BRZ plus oryzalin.

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Table 1. *Overview of cellulose macrofibril orientations*

	Cellulose orientation[a]				
Treatment	transverse	oblique	random	longitudinal	**Number of repeats**
Col-0, upper	1.82±0.70	0.09±0.28	0.08±0.25	1.43±0.63	38
Col-0, lower	1.18±0.56	0.16±0.37	0.05±0.27	1.89±0.51	38
Col-0+EBL, upper	0.42±0.69	0.47±0.77	0.10±0.30	1.53±0.61	19
Col-0+EBL, lower	0.33±0.55	1.40±0.72	0.43±0.63	0.63±0.56	30
Col-0+BRZ, upper	1.48±0.60	0.02±0.09	0.26±0.44	1.82±0.67	31
Col-0+BRZ, lower	0.65±0.49	0.09±0.29	0.17±0.39	1.91±0.29	23
Col-0+ory, upper	0.90±0.84	0.52±0.70	1.22±0.85	1.56±0.73	25
Col-0+ory, lower	0.23±0.44	0.15±0.38	0.77±0.60	2.00±0.00	13
Col-0+ory+BRZ, upper	0.63±0.66	0.22±0.36	1.13±0.67	1.32±0.75	26
Col-0+ory+BRZ, lower	0.20±0.41	0.11±0.32	1.20±0.70	1.90±0.31	20

[a] Cellulose macrofibril orientation across the whole thickness of outer epidermal cell walls was determined using S4B dye, spinning-disc and super-resolution confocal microscopy. The prevalence of each type of cellulose macrofibril orientation in every Z-stack was characterized by scores 1 to 3 as high (3), intermediate (2) or low (1). Then these values were averaged between all Z-stacks for a given treatment and presented as means ± SD.

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Table 2. *Stimulation of gravitropic bending by brassinazole is impaired in the triple* csla2csla3csla9 *mutant compared with* Col-0 *plants*

Comparison	**Time after gravistimulation, hours**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	Stimulation of bending, fold[a]											
Col-0 + BRZ vs. *Col-0*	12.8	13.0	12.4	6.4	3.2	2.5	2.4	1.9	2.0	1.8	1.9	2.0
csla2csla3csla9 + BRZ vs. *csla2csla3csla9*	5.0	4.6	3.2	3.1	2.6	1.8	1.8	1.7	1.7	1.4	1.7	1.5

[a] Gravitropic bending in the presence of BRZ (Fig. 6) was divided by that without BRZ for *Col-0* and *csla2csla3csla9*, respectively.

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Figure legends

Fig. 1. Brassinosteroids affect gravitropism of hypocotyls in Arabidopsis plants. Etiolated *Col-0* seedlings were grown on horizontal Petri plates with one-half strength agarized Murashige and Skoog medium without supplements (A), with 100 nM EBL (B) or 1 μM BRZ (C). Five-day-old plants were photographed.

Fig. 2. Brassinosteroids change cell wall mechanics in Arabidopsis hypocotyls. (A) The schematic representation of regions extended by the creep method (orange shadings) in hypocotyls of different age. Arrowheads mark borders of growing zones in hypocotyls of *Col-0* plants of the respective age. Changes in creep rates by BRZ (1 μM) in hypocotyls of 6-day-old *Col-0* plants (B) and by EBL (100 nM) in hypocotyls of 3-day-old (C), 5-day-old (D) and 6-day-old (E) *Col-0* plants. Creep rates were measured under 750 mg (B, C, E) or 625 mg (D) loads. Data are means ±SE (n=10). Different letters in (B) mark significant differences ($P < 0.05$) revealed by Games-Howell's post-hoc test performed after ANOVA. Asterisks in (C-E) denote significant difference (*$P < 0.05$; **$P < 0.01$) between the respective zones of EBL-grown and control seedlings determined by Student's *t*-test.

Fig. 3. Biochemical composition of cell walls in Arabidopsis plants as affected by brassinosteroids. The levels of uronic acids (A), crystalline cellulose (B) and the monosaccharide composition of cell wall matrix polymers (C) were determined in 5-day-old etiolated Col-0 seedlings without supplements in the growth medium (control), in the presence of 1 μM BRZ or 100 nM EBL. Data are means ±SE (n=9). Asterisks denote significant differences (*$P < 0.05$; **$P < 0.01$) revealed by Dunnett's post-hoc test performed after ANOVA.

Fig. 4. Brassinosteroid and oryzalin effects on the arrangement of cellulose macrofibrils in the outer epidermal cell wall of hypocotyls from 5-day-old etiolated Col-0 Arabidopsis plants. Hypocotyls were extracted under mild conditions and their walls were stained with Pontamine Fast Scarlet 4B, the cellulose-specific fluorescent dye. Cellulose orientation is shown (A) in the upper growing and (D) the lower non-growing region of hypocotyls from control seedlings grown on one-half strength agarized Murashige and Skoog medium without supplements; (B) the upper and (E) the lower region of hypocotyls from plants grown in the presence of 100 nM EBL; (C) the upper and (F) the lower region of hypocotyls from plants grown in the presence of 1 μM BRZ; (G) the upper and (I) the lower

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region of hypocotyls from plants grown in the presence of 250 nM oryzalin; (H) the upper and (J) the lower region of hypocotyls from plants grown in the presence of 1 μM BRZ and 250 nM oryzalin.

Fig. 5. Cellulose orientation affects the percentage of standing Arabidopsis hypocotyls. Col-0 seedlings were grown in darkness on horizontal Petri plates for 5 days without supplements (white bar), with 250 nM oryzalin (orange bar), in each case with 1 μM BRZ (hatched bars) or without (solid color bars). Data are means ±SE (n=6). Different letters denote the significant difference between control and oryzalin-grown plants (P=0.0017; Student's t-test). Asterisks indicate significant effects of BRZ in control or oryzalin-grown seedlings (**P < 0.01; ***P < 0.001; Student's t-test).

Fig. 6. Elimination of glucomannans in the triple *csla2csla3csla9* mutant plants increases gravitropic bending of hypocotyls. Etiolated Col-0 and *csla2csla3csla9* mutant seedlings were grown on vertical Petri plates with or without 1 μM BRZ for 3 days, subsequently gravistimulated by a 90-degree clockwise rotation of the plates, and gravitropic bending of their hypocotyls was followed by an infrared imaging system for 12 h. Data are means ±SE (n=10). Asterisks denote significant differences (*P < 0.05; **P < 0.01; Student's t-test) between *csla2csla3csla9* and Col-0 plants.

Fig. 7. BRZ inhibits cell expansive growth at the base of Arabidopsis hypocotyls. (A) Epidermal cell length distribution along the lower parts of hypocotyls in 55- and 72-hour-old etiolated *Col-0* seedlings grown with 1 μM BRZ or without (control). Cells are numbered from the base of hypocotyls towards cotyledons. Data are means ±SE (n=9). All the cells are significantly shorter in the presence of BRZ than the respective control cells (P < 0.01; Student's t-test) with the exception of cells 1 in 55-hour-old plants (not shown on the plot A). (B) Average cell expansion rates at the base of hypocotyls calculated from the data of plot A (means ±SE, n=9). Asterisks mark significant differences (*P < 0.05; **P < 0.01; ***P < 0.001; Student's t-test).

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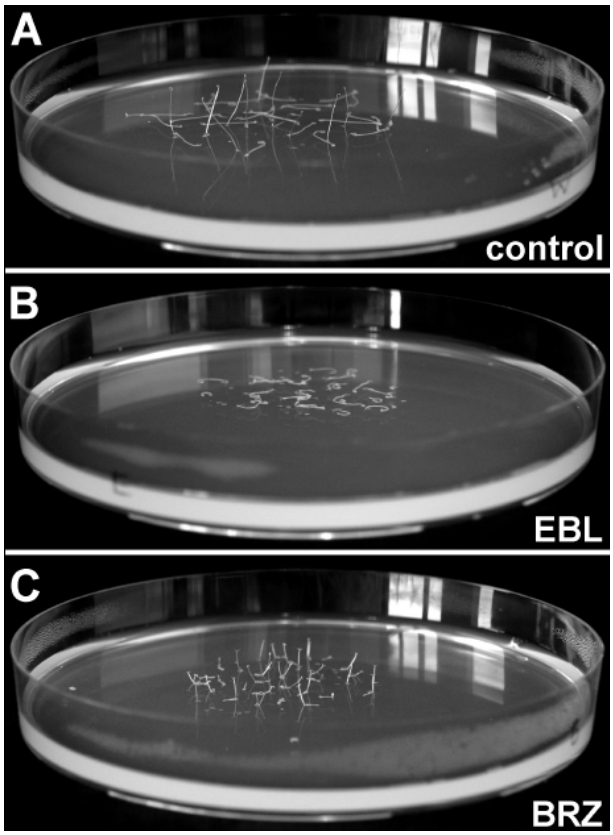

Fig. 1.

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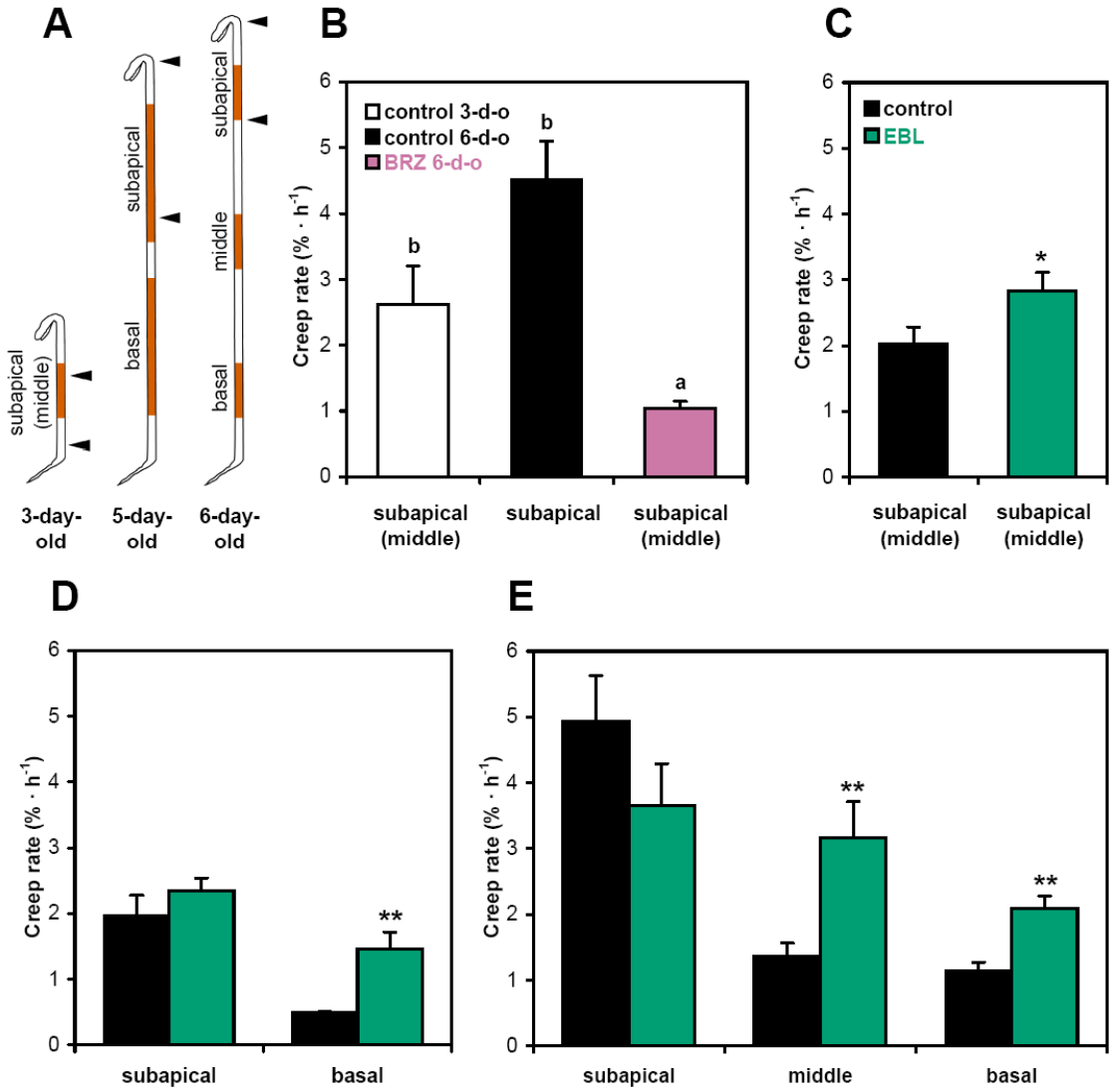

Fig. 2.

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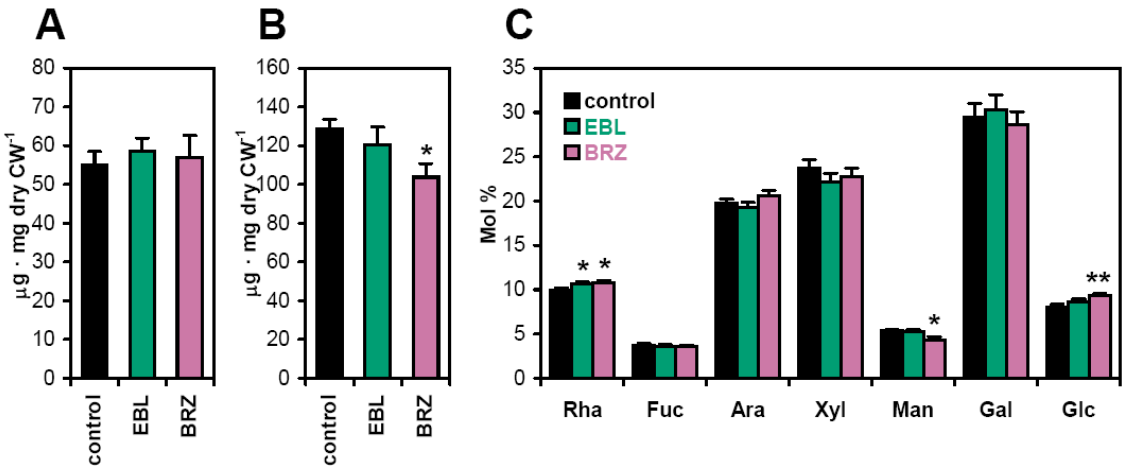

Fig. 3.

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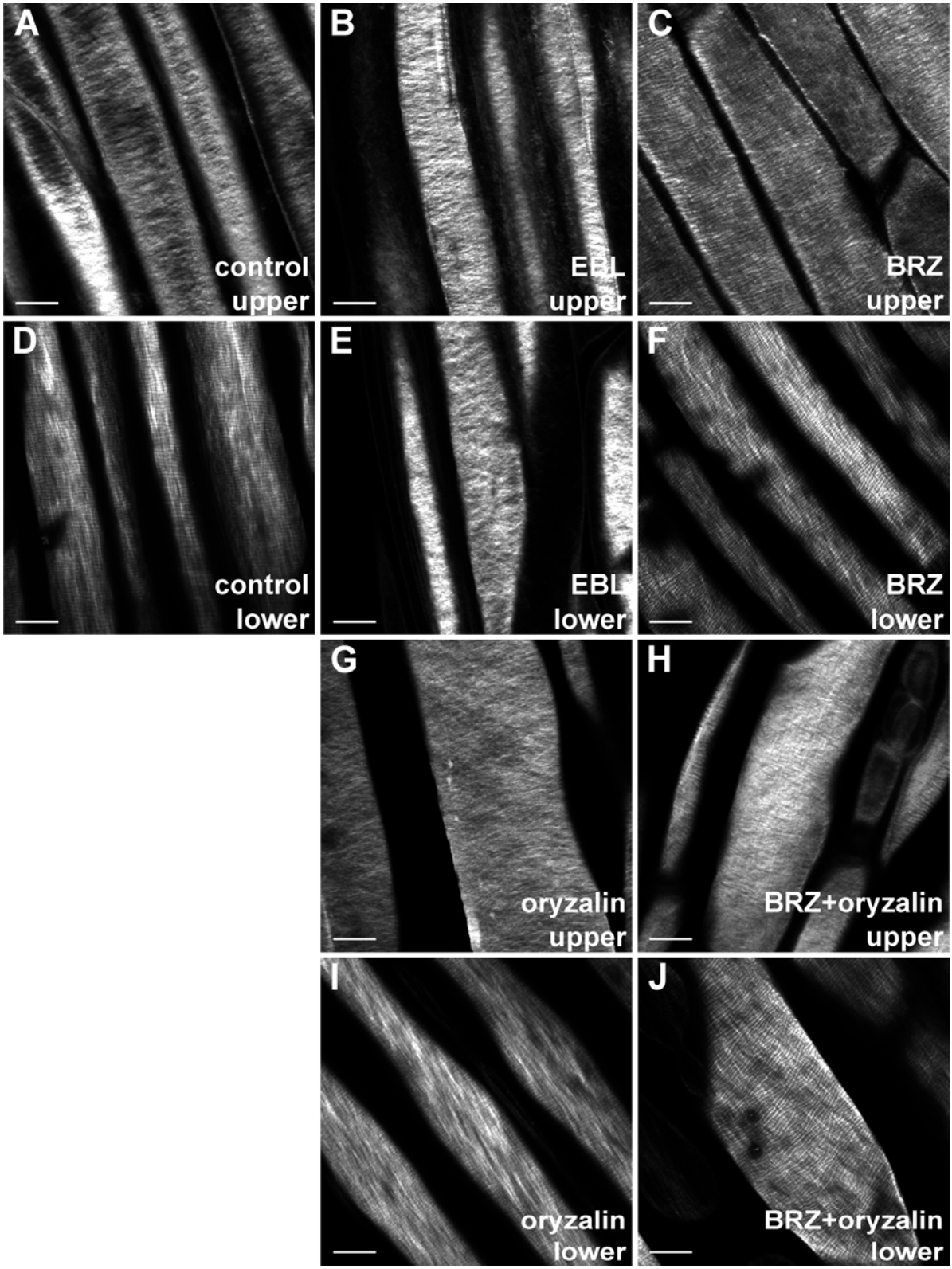

Fig. 4.

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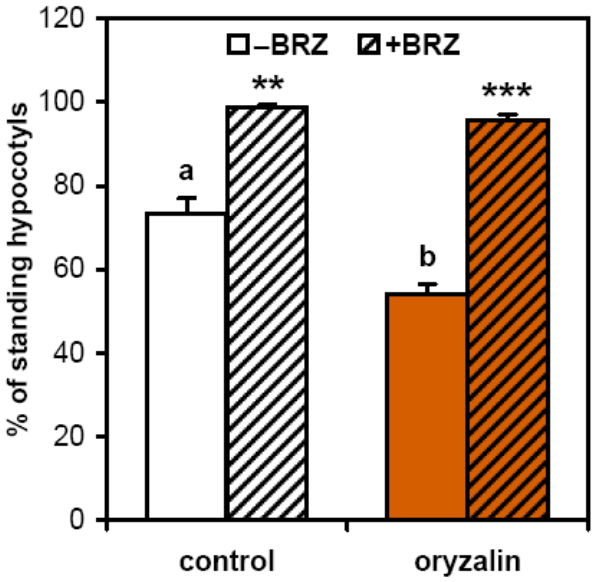

Fig. 5.

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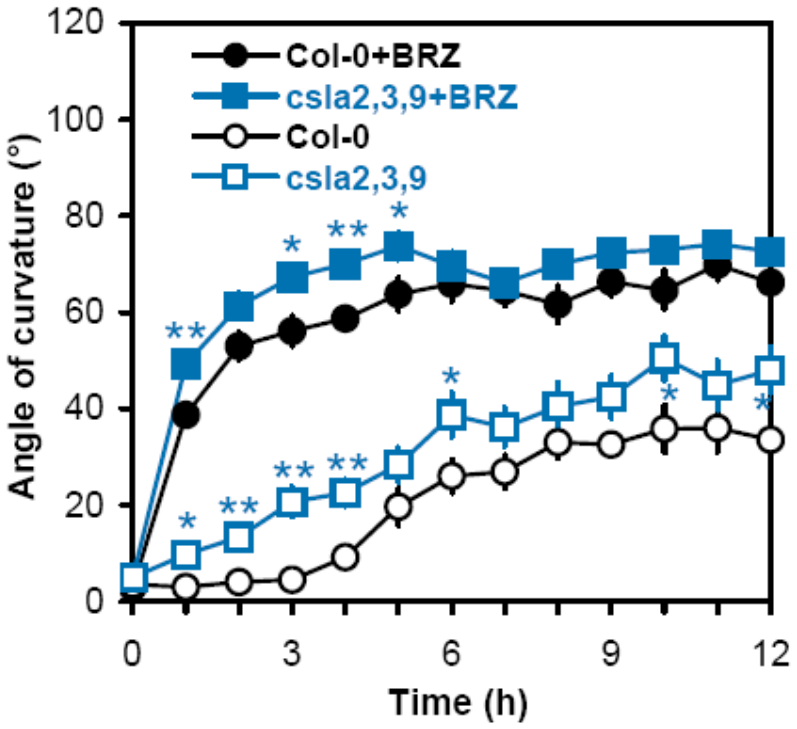

Fig. 6.

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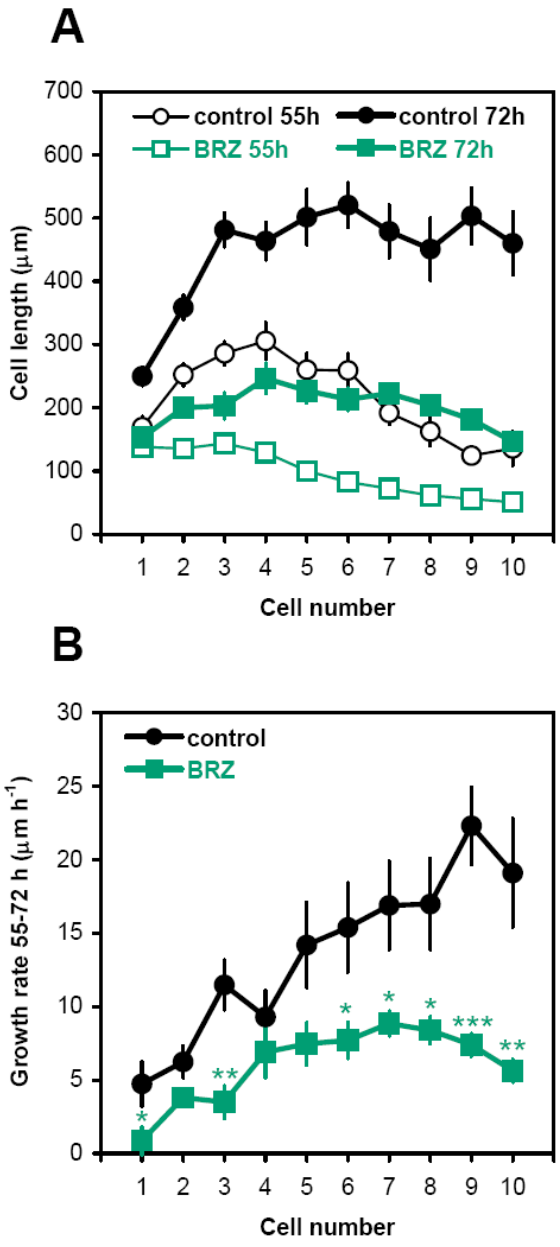

Fig. 7.